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RISK ASSESSMENT OF AIR VERSUS OTHER TRANSPORTATION MODES FOR EXPLOSIVES AND FLAMMABLE CRYOGENIC LIQUIDS. VOLUME I: RISK ASSESSMENT METHOD AND RESULTS

ORI, Incorporated
Silver Spring, Maryland

Prepared for
Department of Transportation
Washington, D. C.

December 1979

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VOLUME I: RISK ASSESSMENT METHOD AND RESULTS

FINAL REPORT

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16. Abstract

This report describes a method for assessing the comparative risks of transporting hazardous materials by alternative routes and modes. The method is then applied to the transport of Class A explosives and liquid hydrogen between specific origin-destinations, testing the air-highway modal combination with alternative combinations of highway, rail, and marine modes. The risks were found to be highly route-dependent; however, for those routes selected, the air-highway modal combination showed generally lower risks. Rerouting and improvement in terminal operations showed the greatest opportunity for risk reduction.

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I. EXECUTIVE SUMMARY

OVERVIEW

ORI, Inc., has performed for the Materials Transportation Bureau, under Contract DOT-RC-82036, a risk assessment study comparing the transport of certain hazardous materials by air with the transport of these materials by alternative modes. The materials analyzed were Class A Explosives (CAE) namely TNT, dynamite, slurries, and blasting caps, and Flammable Cryogenic Liquids (FCL) namely liquid hydrogen, LH_2. Technical assistance was provided to ORI by two private companies that produce these materials, Hercules Aerospace Division of Hercules, Incorporated and Linde Division of the Union Carbide Corporation.

Twelve origin-destination pairs were analyzed, including six each for CAE and FCL (as shown in Figures 1.1 and 1.2). With each origin-destination pair is associated an air route involving air and highway modes, and a non-air alternative involving combinations of highway, rail and marine modes. For each route, three separate risk values have been calculated: injuries, fatalities, and property damage. No attempt has been made to combine these values by means of assigning dollar values to injuries or fatalities.

To obtain large sample sizes of current data concerning shipments, accidents, incidents, severities, and probable losses, numerous sources covering the 1971-1977 time frame have been consulted. These sources include U.S. DOT modal administration data, the Hazardous Materials Incident Reporting

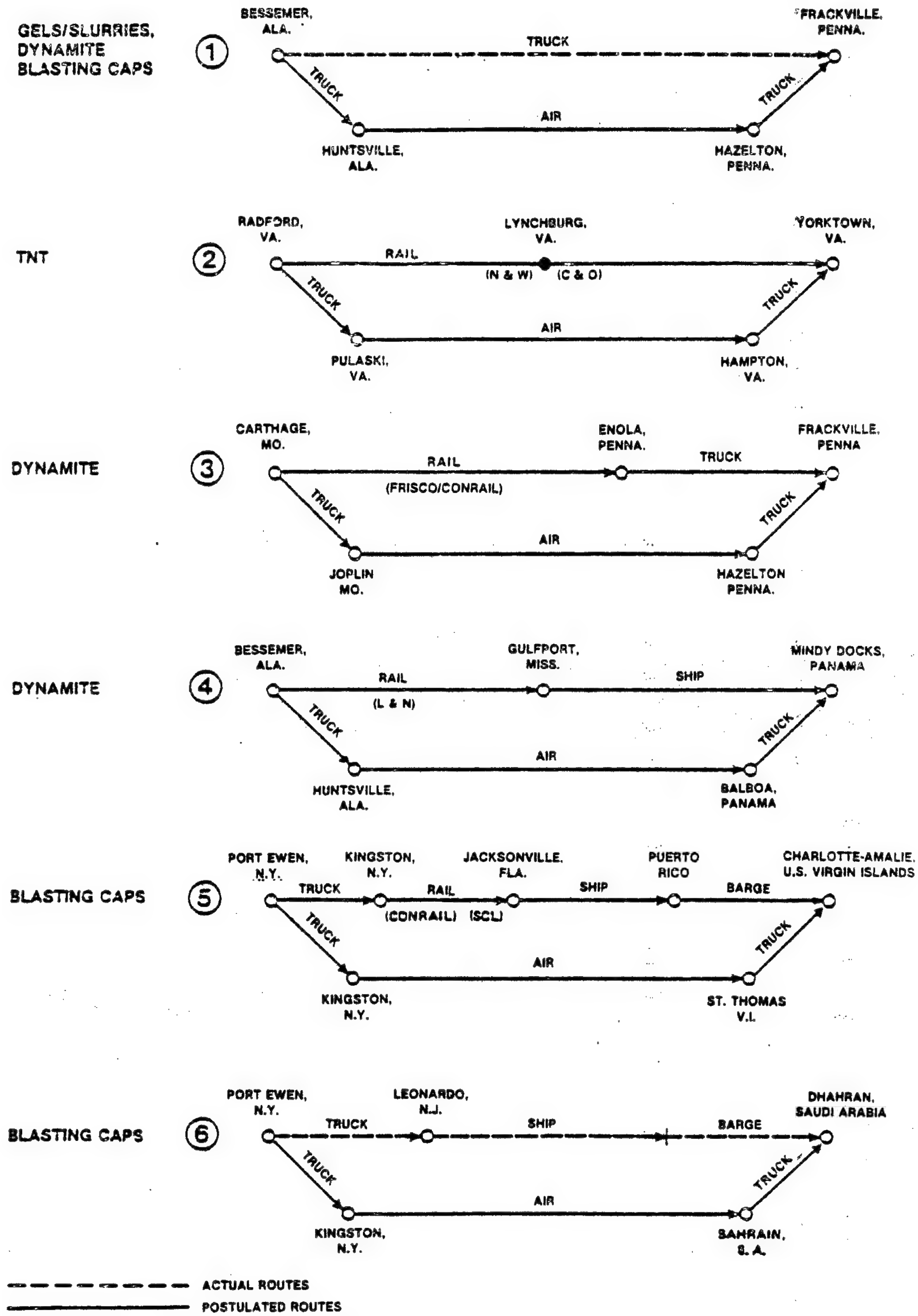

FIGURE 1.1. ORIGIN-DESTINATION PAIRS FOR CLASS A EXPLOSIVES

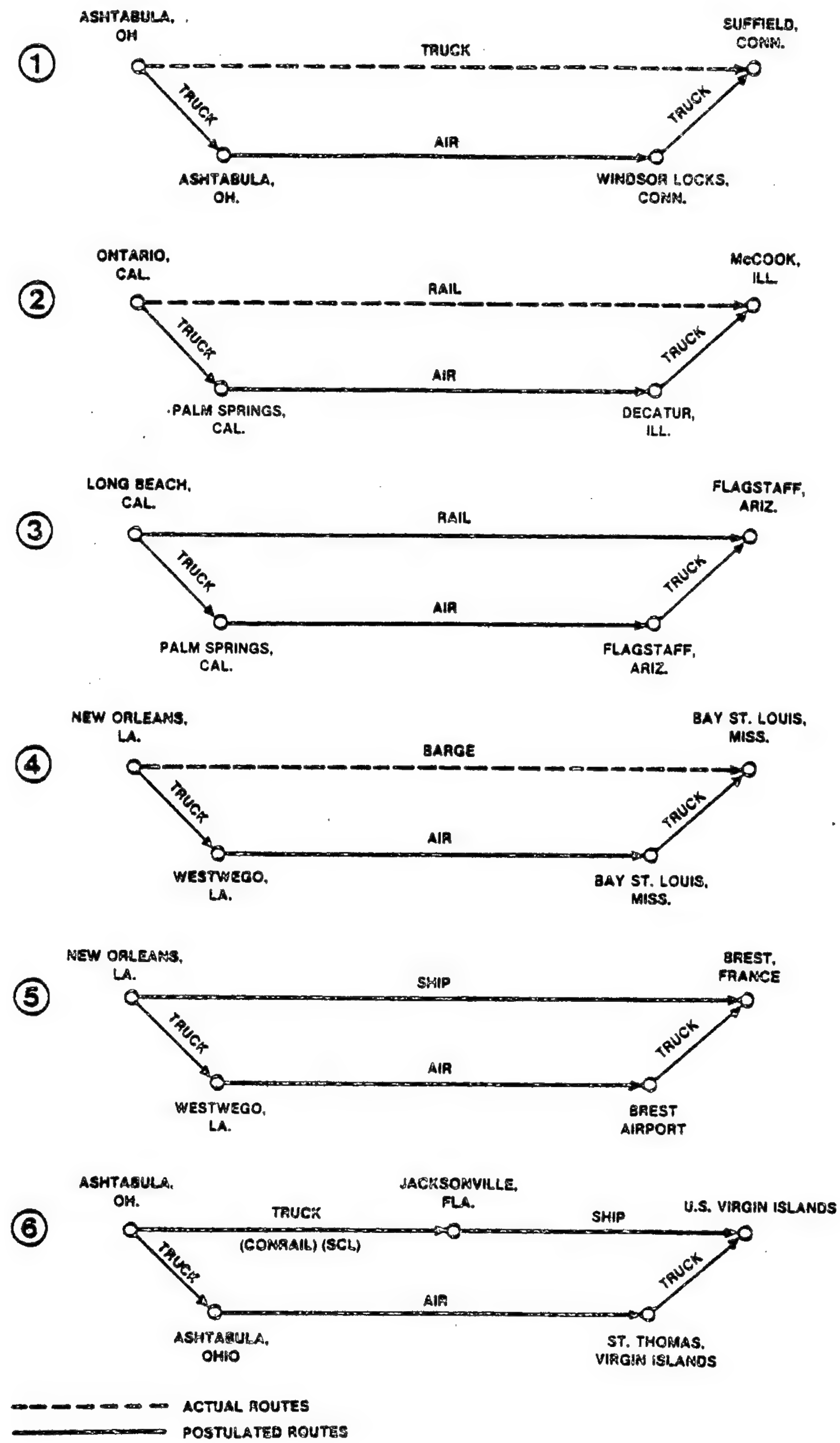

FIGURE 1.2. ORIGIN-DESTINATION PAIRS FOR FLAMMABLE CRYOGENIC LIQUIDS

(HMIR) System, Bureau of Mines, Institute of Manufacturers of Explosives, as well as industry records and numerous other materials.

RATIONALE

The following points should be kept in mind when interpreting the results of this study:

In many instances an origin cannot be connected to a destination by a particular single mode. For example, the air mode always requires truck transport to and from an airport. The required intermodal connections are therefore included in the definition of each mode as applied to a particular origin-destination.

This is a requirement to compare existing operations (e.g., the truck transport of LH_2) with postulated operations that have never been done (e.g., the air transport of LH_2). Historic data are available to define risks of the former, while extensive engineering analyses are used to define the risks of the latter. To the extent possible, this study extrapolates the data from known modes and operations to make estimates for postulated situations. Truck transport data are used as a primary baseline since it has the most extensive data base.

CALCULATING RISK

Route Segments

Total risk or loss for a given route has been found by dividing the route into segments where the risk is expected to change. Thus, a segment is defined by a particular phase of operation for the mode in question and a particular set of exposure characteristics attributable to the geographic location of a given operation phase for each mode. Exposure characteristics are considered to change with each new county through which the route progresses, as well as with each terminal area (e.g., rail yard, airport, etc.) within a county traversed by the route. As an example, a truck-air-truck route alternative would have separate segments associated

with: (1) each operation phase of the first truck link--loading, in-transit and unloading, (2) each different county traversed during the truck in-transit phase, (3) each operation phase of the air link -- loading, static, taxi, take-off, in-flight, landing, taxi, static, and unloading; (4) each different county traversed during the air in-flight phase; (5) each operation phase of the second truck link--loading, in-transit, unloading, and, (6) each different county traversed in the second truck in-transit phase. Risks are computed for each segment along the route and the separate risk values are then aggregated to produce a risk value for the entire route.

Expected Value Model

The risk calculation for any given segment is determined by an expected value risk model. It computes the probable number of injuries, fatalities, and dollars of property damage associated with the transport of a certain amount of CAE or FCL material, summed over all possible events.

"Expected value" is defined as the likelihood of a loss-generating event times the amount of loss resulting from that event. In this model, all loss events must be preceded by an incident: splash, fire, explosion, or fireball. And, since all possible occurrences leading to loss events must be considered, the model requires a summation of the expected value of loss for each incident type. The following expression defines this relationship between loss event probability and loss measure for a given segment.

$$R(s) = \sum_{ijk} L(i)sL(j/k)L(k/j)C(jk)s$$

where

$L(i)s$ = likelihood of accident type i in segment s

$L(j/i)$ = likelihood of incident type j given accident type i

$L(k/j)$ = likelihood of loss in severity level k, given incident type j

$C(jk)s$ = potential loss associated with severity level k and incident type j in segment s.

In the context of this study, an accident has been defined as an event which leads to an incident; a derailment, the dropping of a package in handling, or the malfunctioning of a valve are examples. It may be noted that this definition departs somewhat from the definitions ordinarily used to tabulate modal accidents, since accidents as defined herein need not involve damage to the vehicle, persons, or property. Instead, accidents are considered to be any occurrence that precipitates an incident (i.e. unintentional release of material).

A severity level is defined as one of three radii: 1) the closest radius characterized by the most severe effect; 2) an intermediate radius with moderate severity; and 3) the farthest radius with least effect greater than zero. Loss depends on exposure of personnel, other persons, and property within these various radii. Thus, the path for arriving at one value for expected loss is from one accident type, to one incident type resulting from that accident, to one severity level radius resulting from that incident type, to the potential loss in persons or property within that radius. This path represents only one combination of events which will result in loss of a segment; all other paths are accounted for via the summation function.

Model Input Data

Inputs to the model were of two types: 1) likelihood values and exposure (potential loss) values for each mode, phase, material amount, and segment location; and 2) segment definitions in terms of terminal exposure, mileage, and county. Likelihood values were found using the accident reports from the respective modal agencies and the incident reports from the Materials Transportation Bureau (U.S. Department of Transportation). In addition, published human and property tolerance levels for incident effects from hazardous materials rule-makings and from industry research were also factored into the estimates. Exposure values were derived from industry information about terminal facility configuration and density, from (modal) industry publications, through personal contact with port facility personnel, from information about population and property densitities from the U.S. Bureau of

the Census, and from information about severity radii made available through industry experts and National Bureau of Standards specifications.

Pivotal Assumptions

Throughout the development and application of the risk assessement model, it was necessary to make a number of assumptions in order to simplify certain model inputs. Key among these are the following:

Accident Rates. The accident rate for vehicles carrying hazardous materials is assumed to be the same as the accident rate for vehicles carrying general commodities. There is no "carefulness" factor included in the accident likelihood values which are used.

Population and Property Density. Population and property value densities are distributed uniformly over an entire county. While this assumption excludes actualities such as greater density along highway routes than rail routes, it facilitates modularization of vast amounts of input data through the use of available county statistics.

Severity Impact. All persons are assumed to be affected by an incident as if they were standing in the open. Similarly, all property is treated from the standpoint of damage as standardized dwelling units, except for cryogenic tank trucks, tank cars, and tank barges which are more resistant.

Direct Costs. Only those persons or property initially affected by an incident are used to calculate costs or losses; costs such as subsequent loss of business revenues or expenses incurred through evacuation are considered indirect and are not included.

Computer Applications

Although the same expected-value risk model was used for both CAF and FCL, a limited set of combined accident-incident sequences were assumed directly for FCL. These assumptions were made after extensive engineering analysis, rather than compute the sequence from insufficient sample sizes.

Through use of this technique, it was found that risk computations could be done manually for FCLs' while computerization was required for CAEs. The use of both the manual and computer techniques in the application of the expected value model shows its versatility. The more emphasis that is placed on modules, the more easily the model can be used for quick, manual calculations. Where it is necessary to consider all possible combinations of discrete events, the model is easily adaptable to computerization.

CONCLUSIONS

Based on a segment-by-segment analysis for each of the twelve origin-destination pairs and on calculations derived from the risk assessment model (see Tables 1.1 and 1.2), the following conclusions have been drawn.

1. Relative Risks Among Modes are Highly Route-Dependent. The comparative risk assessment model ultimately compares entire alternative routes for a given origin-destination pair. Route comparison requires assessment of modal combinations such as truck-air-truck or rail-barge-rail, not exclusive modes. In turn, such comparisons incorporate different cargo capacities and crew sizes, and include different rights-of-way through different population centers. The comparative risk assessment, therefore, is highly route- dependent.

The influence that particular routes exert on risk measures is further evidenced by the fact that risk measures -- injury, fatality, property damage -- may also vary within the same mode. For instance, marine fatality risk might be higher than injury risk along one route and lower than injury risk on another. This relationship among risk measures is due to the severity level vs. the population density associated with the three (modularized) severity radii.

TABLE 1.1

RISKS ASSOCIATED WITH CAE ROUTES

Origin-Destination	Route Alternative	Risk (per shipment of 49.5 tons of dynamite)		
		Injuries	Fatalities	Property Damage ($)
Bessemer, ALA to Frackville, PA	Non-air (highway)	5.49×10^{-4}	4.95×10^{-4}	50
	Air alternative	1.69×10^{-4}	1.44×10^{-4}	153
Radford, VA to Yorktown, VA	Non-air (rail)	1.45×10^{-4}	1.21×10^{-4}	399
	Air alternative	2.04×10^{-4}	2.28×10^{-4}	192
Carthage, MO to Frackville, PA	Non-air (rail-hwy.)	3.94×10^{-4}	2.94×10^{-4}	893
	Air alternative	1.14×10^{-4}	1.67×10^{-4}	172
Bessemer, ALA to Mindy Docks, Panama	Non-air (rail-ship)	7.04×10^{-4}	1.49×10^{-3}	5,937
	Air alternative	1.73×10^{-4}	2.20×10^{-4}	176
Port Ewen, NY to St. Thomas, VI	Non-air (rail-ship)	1.58×10^{-3}	2.22×10^{-3}	8,872
	Air alternative	8.56×10^{-5}	9.75×10^{-5}	172
Port Ewen, NY to Saudi Arabia	Non-air (hwy-ship)	2.02×10^{-3}	2.78×10^{-3}	7,699
	Air alternative	8.65×10^{-5}	$9,80 \times 10^{-5}$	172

TABLE 1.2

RISKS ASSOCIATED WITH LH_2 ROUTES

Origin-Destination	Route Alternative	Risk (per shipment of 250,000 gallons)		
		Injuries	Fatalities	Property Damage ($)
Ashtabula, OH to Suffield, CONN	Non-air (highway)	2.1×10^{-2}	7.0×10^{-2}	431
	Air alternative	3.0×10^{-3}	4.0×10^{-3}	538
Long Beach, CA to Flagstaff, AZ	Non-air (rail)	1.0×10^{-2}	7.0×10^{-3}	805
	Air alternative	9.0×10^{-3}	5.8×10^{-3}	604
New Orleans, LA to Bay St. Louis, MISS	Non-air (marine)	3.2×10^{-2}	2.3×10^{-2}	2,208
	Air alternative	0.7×10^{-2}	1.5×10^{-2}	532
New Orleans, LA to Brest, France	Non-air (marine)	8.0×10^{-3}	1.4×10^{-2}	5,184
	Air alternative	9.0×10^{-3}	1.5×10^{-2}	931
Ontario, CA to McCook, ILL	Non-air (rail)	3.3×10^{-2}	1.7×10^{-2}	1,871
	Air alternative	1.3×10^{-2}	2.0×10^{-2}	738
Ashtabula, OH to St. Thomas, VI	Non-air (highway)	2.6×10^{-2}	9.2×10^{-2}	5,360
	Air alternative	2.0×10^{-3}	2.0×10^{-3}	641

2. Rerouting Can Significantly Lower Risks. Because of the route-dependent nature of the risk measurements, it was found that rerouting of a shipment to avoid high population density segments can reduce risk for each of the modes. For example, rerouting of an LH_2 shipment to avoid Cook County, Illinois, dramatically reduced both air and rail risk measures.

3. With Proper Attention to Airport Selection, Airport Handling and Related Highway Staging Operations, the Risk of Shipping Hazardous Materials By Air Can Be Made Significantly less Than That for Other Modes. Despite the fact that the risk assessment model compares routes and not modes exclusively, the majority of the route alternatives involving the air mode (i.e., truck-air- truck) have resulted in the lowest risk estimates for injuries and fatalities for the types of hazardous materials studied. The air routes, however, generally have higher property damage losses due to airport terminal areas. In addition, the highway portions of the air routes contribute more to the injury and fatality levels (more than air).

The chief reason for the lower air risks is due to the low risk characteristic of the in-flight phase. A corollary of this relationship is that air is relatively safer over longer distance routes, since its risks are more nearly dependent upon departure rate and are less distance-related.

4. Rail Risks are Dominated By Terminal Area Risks. With rail-oriented route alternatives, relatively high population densities surrounding rail terminal areas account for high probabilities for all three risk measures: injuries, fatalities, and property damage. Also, rail risks are assumed to be high, by an amount undetermined in this study, because of the possibility of propagating accidents involving hazardous materials, i.e., multiple and often consecutive rail cars carrying different hazardous materials.

After total risks for the various routes were calculated, the sensitivity of these estimates was tested for certain safety improvement measures. In one instance, the impact of increased rail car inspection (both vehicle and material-related) on the lowering of risks was shown to be rather small (see Attachment A).

5. Marine Risks are Dominated by Terminal Facility and by Vessel Cargo Losses. For marine route alternatives, the large amounts of material carried on a single vessel (i.e., barge or ship) plus the loss potential at marine terminal facilites dominate the marine mode risks. The highway portions of marine routes also contribute significantly to the overall risks.

6. Highway Risks are Dominated by Truck Accident Rates and by Population Densities. The relatively high truck accident rate and the dense populations through which highways travel give the highway mode a relatively high risk, particularly with regard to injury and fatality measures. The highway portions of both the air and non-air route alternatives show the high risk contributed by the highway mode.

RECOMMENDATIONS

Due to many complex and varied inputs, as well as the simplifying assumptions required to calculate disparate risks, it is recommended that a number of steps be undertaken by the Materials Transportation Bureau to expand upon the research accomplished in this contract study.

1. Capitalize on Existing Efforts. Because of the flexibility and computerization of the risk assessment model DOT should consider combining the ORI model with available on-line data bases.

2. Assess Impacts. As presently structured, the model is sensitive enough to evaluate the impact of improved modal operations such as increased

track inspection. DOT may find it useful to analyze in more detail the impact of this and other safety related measures.

3. Analyze Propagating Accidents. Actual rail operations often ship directly adjacent carloads of hazardous materials, including different hazardous materials. The risk potential of numerous and adjacent carloads on a single train were not addressed in this risk assessment study. Further risk assessment efforts should deal with the impact of such multiple shipments.

4. Refine Demographic Inputs. The use of county data to correspond with discrete segment risks was an important element of the overall study. It allowed potentially vast amounts of input data to be more readily managed. On the other hand, average density figures may overstate (understate) loss values somewhat; while requiring additional resources, more precise estimates could be obtained by refining densities to reflect differing population and property patterns.

II. INTRODUCTION

STUDY PURPOSE AND OBJECTIVES

The study which this report describes has been conducted for the purpose of assisting the Materials Transportation Bureau (MTB), U.S. Department of Transportation, in its evaluation of the comparative risks of transporting selected hazardous materials by different modes. Specifically, MTB is concerned with comparing the risks involved in air transport of flammable cryogenic liquids and of Class A explosives with the risks of transporting these materials by non-air mode combinations. This study is designed to provide information which MTB can use to carry out more effectively its functions in the following areas:

- Determining the adequacy of existing regulations in Title 49, CFR, Parts 100-179

- Evaluating safety analyses submitted with exemption petitions

- Finding a rational means of comparing air shipment risks with those of shipments by other modes.

The objective of this study is to perform a comparative risk assessment specifically for the air transport of flammable cryogenic liquids and Class A explosives by carrying out the following steps:

1. Determine the accident and normal shipment experience for air, rail, highway, and marine modes (Tasks 1.1 and 2.1)

2. Determine the risk factors which are significant for each material and each mode (Tasks 1.2 and 2.2)

3. Determine the most appropriate method for comparatively assessing the risks of air, rail, highway and marine mode transport of each material (Tasks 1.3 and 2.3)

4. Use this method to compare the risks of air transport with those of non-air mode transport of the materials in question for certain specified origins and destinations and identify the least risk route (mode combination) (Tasks 1.4 and 2.4).

Tasks 1.1, 1.2, 1.3, and 1.4 involve Class A explosives (CAEs); Tasks 2.1, 2.2, 2.3, and 2.4 involve flammable cryogenic liquids (FCLs). The above steps have been carried out under the following additional constraints:

- The methodology developed and implemented in Steps 3 and 4 must be capable of addressing terminal as well as in-transit operations and must consider all parties exposed to risk including vehicle (aircraft, vessel) operators, emergency response personnel, the public, and exposed property.

- The methodology must address risk factors associated with transporting CAEs and FCLs by each mode including number and size of shipments, type of packages, inherent characteristics of the materials, normal and accident conditions (or "environments") within each mode, and demographic factors associated with each mode.

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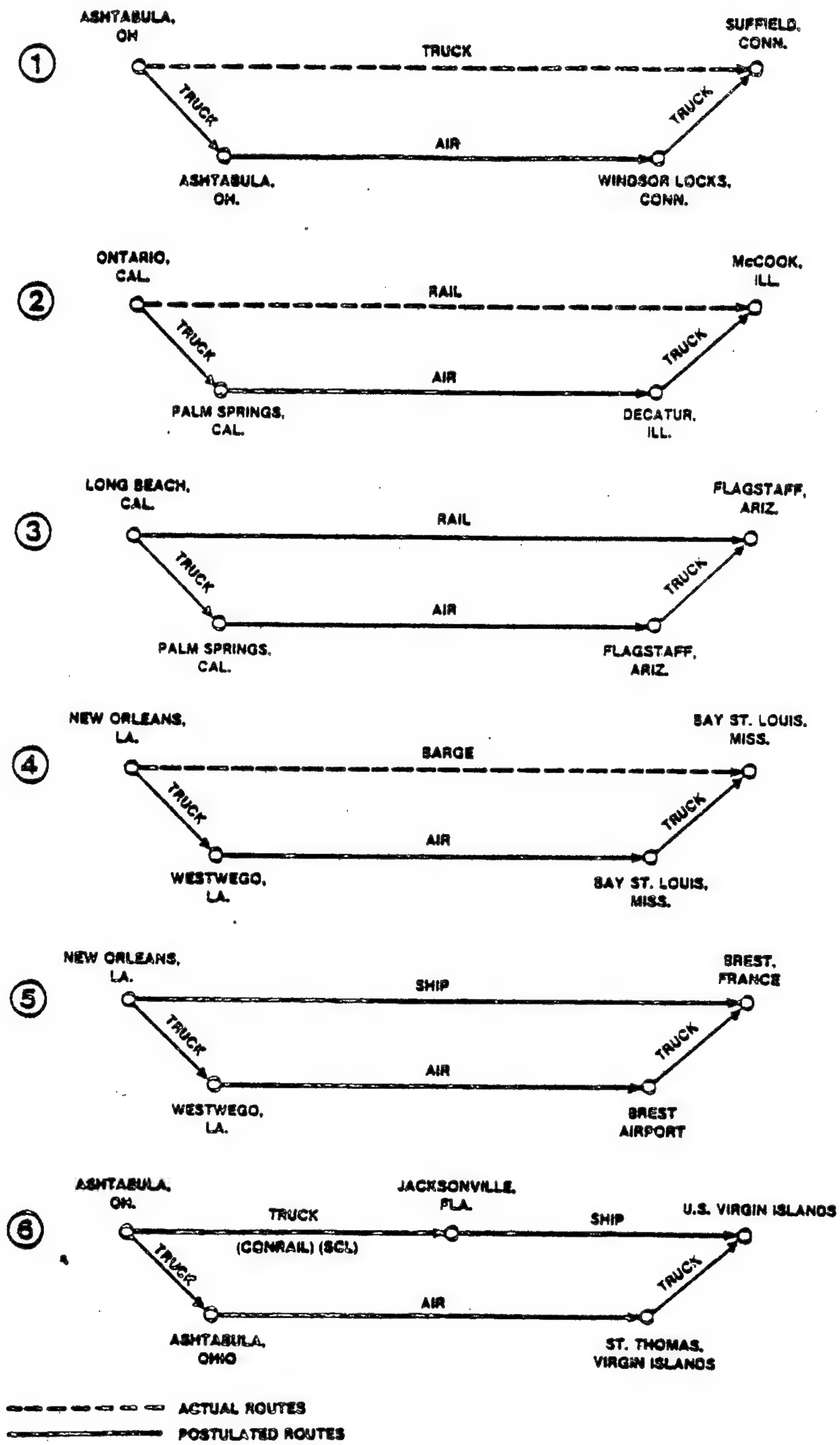


FIGURE 2.2. ORIGIN-DESTINATION PAIRS FOR FLAMMABLE CRYOGENIC LIQUIDS

route where the risk may be expected to change. Aggregation of segment risks produces risk over an entire route.

Quantification of Risk

The expected value of risk for a particular segment is a product calculated as the likelihood of an incident times the loss associated with such an incident (where an incident is a release of hazardous material and loss is comprised of injuries, fatalities, and property damage). Values for incident likelihood and loss are found using a combination of empirical and analytical data.

Study Outputs

This study has produced three types of information: 1) a comparative risk assessment methodology; 2) the values associated with incident likelihood and loss level for each mode and material (necessary inputs for the expected value model); and 3) quantified estimates of risk for representative routes.

ORGANIZATION OF THIS REPORT

This report is organized as described herein. Volume I contains a thorough description of the risk assessment methodology, an example of the step-by-step implementation of that methodology, and the results of the risk assessment for the twelve representative origin-destination pairs (Sections III, IV, and V, respectively). Volume II contains the likelihood and loss values mentioned above as they were developed for each mode, material, and route. Specifically, Sections II, III, IV, and V of Volume II describe likelihoods associated with each mode; Section VI describes mode characteristics used to arrive at some of the likelihoods associated with mode-material combinations described in Sections VII and VIII; and Section IX describes loss level values as they have been developed for the specific routes. Thus, Volume II can be thought of as a final report on accident and normal shipment experience, and mode/route/material risk factors (Tasks 1.1, 1.2, 2.1, and 2.2); Volume I documents the methodology development and implementation (Tasks 1.3, 1.4, 2.3, and 2.4).

ANALYTICAL ASSISTANCE

The following organizations contributed substantially to the modeling of the incident likelihoods and the effects of incidents involving certain hazardous materials:

Air Products and Chemicals, Inc. (FCL barge operations)

Hercules, Incorporated, (CAE characteristics, incident severities and transport operations)

Union Carbide Corporation, Linde Division (FCL characteristics, incident severities, and transport operations).

Hercules and Linde contributions have been referenced throughout Volume II and its appendices.

III. RISK ASSESSMENT METHODOLOGY

The risk assessment methodology used in this study consists of several parts. It includes the selection of risk measures, the development of a model to estimate values for these measures, the gathering and analysis of data to be used in the model, the refinement of the model to facilitate comparison among modes, and the implementation of the model to obtain risk comparisons over specific routes. Injuries, fatalities, and property damage have been selected as the measures of risk. While Volume II describes the gathering and analysis of input data and Sections IV and V of Volume I explain the model's implementation and results, this section describes the development of the model and its use in comparing modes. In addition, this section points out some contributions of the study to risk assessment state-of-the-art.

THE EXPECTED VALUE MODEL

In order to measure the number of injuries, fatalities, or dollars of property damage associated with the transport of a certain hazardous material, it is necessary to define the route (modes and locations) over which that material is transported. For the purpose of this study, it has been assumed that risk would change along a route according to the phase of transport operation underway and according to the demography associated with each phase. Therefore, risk values are determined separately for each segment and are then summed across all segments for an entire route.

The expected value model for determining risk is applied at the segment level. According to this model, "risk" is the product of a level of loss for a segment (in injuries, fatalities, or dollars of property damage) and the likelihood of incurring that level of loss.

The likelihood of incurring a certain level of loss is really the product of three likelihoods: that of an accident, the probability of an incident given an accident, and the probable severity level given that incident. Thus, the value for a particular risk measure in segment s is given as

$$R(s) = \sum_{ijk} L(i)s \cdot L(j/i) \cdot L(k/j) \cdot C(jk)s$$

where $L(i)s$ = likelihood of accident of type i in segment s,

$L(j/i)$ = likelihood of incident of type j given an accident of type i,

$L(k/j)$ = likelihood of severity level k given incident of type j, and

$C(jk)s$ = loss associated with severity level k for incident of type j in segment s.

The summation function accounts for all possible combinations of accident type, incident type, and severity level -- and, thus, for all possible ways of incurring a loss.

"Accidents" are those events during any part of a shipment which are potential causes of incidents. "Incidents" are unintentional releases of hazardous materials. "Severity levels" are usually described in terms of injury, fatality, and damage radii with respect to incident location. "Loss" is the number of fatalities, injuries, or property damage dollars which can be attributed to the hazardous material involved in the incident.

Accidents, incidents, and severities are each divided into types or levels in order to be able to account for the peculiarities of specific routes which are found within each segment. For example, the overall likelihood of an incident given an accident is different from the particular likelihood of

an incident given a certain type of accident. Different segments of a route (such as the yard operations segment of a rail route) may show a greater likelihood of a certain accident type (such as collisions) than is inherent in the average accident likelihood for all types. This will affect the likelihood of an incident in that segment and will therefore affect the risk.

It may be noted that the model is based on a concept of progression from accident to incident to effect on geographical area. In this study the step from accident to incident involves a basic assumption: the chance of a carrier becoming involved in an accident is independent of the type of cargo being carried. That is, the multiplication of the two accident and incident likelihoods implies that the all-commodities accident likelihood is equal to the hazardous material accident likelihood. Actually, the latter may be slightly lower; but, since little information is available from which to construct accident rates specific to hazardous material shipments, it was considered more reliable to use general commodity accident data. The "carefulness" factor associated with the operation of a hazardous material vehicle cannot be determined at this time through either inspection of existing data or engineering analysis.

The expected value model is made up of four submodels: three submodels are used to compute the likelihood values, L(i)s, L(j/i), and L(k/j), and a fourth submodel is used to compute the value of loss, C(jk)s. The following descriptions explain in more detail the development and application of these submodels.

LIKELIHOOD OF AN ACCIDENT OF TYPE I IN SEGMENT S, (L(i)s)

A separate route segment is associated with each <u>phase of operation</u> of hazardous materials transport. However, the delineation of phases differs slightly between CAEs and FCLs. For instance, with FCLs "handling" or loading/unloading is considered a separate phase of operation for each mode. With CAEs, the complexity of the handling phases and the frequently long distances covered by the operation have made it necessary to analyze CAE

handling as a separate "mode," not as an operation phase associated with each mode.

For CAEs the likelihood of a given accident type during a specific phase of operation is the product of the accident rate for that type and phase (accidents per shipment unit) times the number of shipment units in question (except for the handling mode); for a line-haul or in-transit phase the shipment unit is one mile; for stationary phases the shipment unit could be, for example, a departure, or, a car shipped. For the CAE handling "mode" the likelihood of an accident during a certain phase of operation (say, forklifting) is computed via the following expression:

$$L(i)s = 1 - (1-p)^n$$

where p = the likelihood of an accident during one handling unit (one forklifting of a pallet) and n = the number of handling units needed to complete segment s (the number of forkliftings needed to load or unload all of the pallets being considered).

For FCLs the likelihood of a given accident type during a specific phase of operation is, again, shipment units times accident rate. This rate is derived by a more complex method, as described in Volume II, Section VIII. With FCLs only certain accident types are considered for the non-handling phases; and handling phase accident likelihoods are related to certain combinations of ill-advised activities, rather than to the more conventional concept of "accidents."

In addition to the accident types conventionally defined for each mode by respective safety reporting requirements, this study has also defined a "dangerous environment" accident type for the air, rail, marine, and highway modes for both CAEs and FCLs. This accident type accounts for certain combinations of temperature, shock, etc., that may be enough to cause the release or ignition of the hazardous material cargo even when no accident has occurred. Obviously, different dangerous environment accident rates are inherent in CAE and in FCL transport. It may be noted that handling-related accidents are assumed to cover all possible incident-producing

situations and, therefore, the "dangerous environment" accident type was not considered for FCL or CAE handling.

Tables 3.1 through 3.6 show accident rates associated with each mode by type and phase of operation for CAEs. Accident rates used for the transport of FCLs are not given for all combinations of phase and type, but are included as elements of the incident rates associated with reasonable scenarios of incident occurrences. Accident rates and likelihoods are discussed in greater detail in Volume II, Sections II through VIII.

To summarize, L(i) is found for each accident type i in segment s (that is, in the phase of operation associated with segment s, by converting the accident rate for the type and phase to an overall accident likelihood). For FCLs this is accomplished by converting the incident rate, which includes the accident rate for each of the selected scenarios, to incident likelihood. To complete this approach, it is necessary to know the number of shipment units in question for segment s in order to determine likelihood. For Class A explosives this study has defined 49.5 tons as the amount being transported along any of the routes. This amount can be carried in one rail car, three trucks, three containers, one cargo aircraft, one break-bulk ship, or one barge (the ship and the barge will have other cargo -- possibly explosives -- in the same shipment, as they have capacities many times larger than those of the other carriers). During the handling mode, this amount is given as 55 pallets of 36 boxes each, or 1980 single boxes. Therefore, the number of shipment units in segment s is either the number of operations, the number of route miles, or, in the case of a highway in-transit segment, the number of vehicles (3) times the number of miles.

For FCLs it was not as simple to find an amount of material for which two routes involving different modes could be compared. A tank truck carries 12,160 gallons, a rail tank car carries 28,300 gallons, and a tank barge carries 250,000 gallons. A roll-on/roll-off ship and a cargo aircraft have been assumed to carry 3 tank trucks. Therefore, the amount used for comparison must be at least 250,000 gallons in order to allow each mode to function most efficiently. This amount equals approximately 8.8 rail car loads (each transported separately), 20.7 truck loads (transported in groups

TABLE 3.1

HIGHWAY ACCIDENT RATES BY ACCIDENT TYPE

Accident Type	Fraction of Total Accidents	Overall Accident Rate (Accident per Vehicle Mile)	Accident Type rate
Collision w/truck	.132	8.33×10^{-7}	1.10×10^{-7}
Collision w/auto	.416	8.33×10^{-7}	3.46×10^{-7}
Collision w/fixed object	.087	8.33×10^{-7}	$.725 \times 10^{-7}$
Collision w/train	.010	8.33×10^{-7}	$.0833 \times 10^{-7}$
Collision w/bus	.003	8.33×10^{-7}	$.0250 \times 10^{-7}$
Collision w/other	.071	8.33×10^{-7}	$.591 \times 10^{-7}$
Overturn	.085	8.33×10^{-7}	$.708 \times 10^{-7}$
Ran off road	.119	8.33×10^{-7}	$.991 \times 10^{-7}$
Jacknife	.048	8.33×10^{-7}	$.400 \times 10^{-7}$
Separation of units	.002	8.33×10^{-7}	$.0167 \times 10^{-7}$
Dangerous Environment CAE	N/A	N/A	6.03×10^{-7}

TABLE 3.2

RAIL ACCIDENT RATES BY TYPE AND PHASE OF OPERATION

Accident Type	Origin Terminal (2 couplings, 1 switching, 12 hours)	Destination Terminal (1 Switching 6 hours)	Yard Operation (1 yarding, 5 switching, 5 coupling, 12 hours)	Line Haul (1 transit) (Per car mile)
Collision	4.31×10^{-5}	2.49×10^{-5}	4.44×10^{-4}	1.99×10^{-7}
Derailment	1.61×10^{-5}	1.08×10^{-5}	4.93×10^{-4}	1.26×10^{-6}
Other	1.52×10^{-6}	2.54×10^{-6}	4.32×10^{-6}	1.07×10^{-7}
Dangerous Env. (CAE) (FCL)	3.65×10^{-5} 1.61×10^{-4}	1.82×10^{-5} 8.02×10^{-5}	3.62×10^{-5} 1.61×10^{-4}	1.22×10^{-7} 5.62×10^{-7}

TABLE 3.3

AIR ACCIDENT RATES BY TYPE AND PHASE OF OPERATION

Accident Type / Phase of Operation	Impact-No fire (i_1)	Impact-Fire (i_2)	No Impact-Fire (i_3)	Dang. Env. to CAE
Static (accidents per departure)	2.30×10^{-8}	neg.	$.62 \times 10^{-7}$	neg.
Taxi	2.68×10^{-8}	neg.	2.45×10^{-8}	neg.
Take-off	2.00×10^{-7}	2.34×10^{-7}	neg.	neg.
In-Flight (accidents per mile)	2.57×10^{-10}	2.40×10^{-10}	2.11×10^{-11}	3.77×10^{-7}
Landing	3.96×10^{-7}	5.49×10^{-7}	neg.	3.64×10^{-7}

TABLE 3.4

MARINE ACCIDENT RATES BY TYPE AND PHASE OF OPERATION:
TUG BARGE ARRAYS

Phase of Operation / Accident Type	Moored (cas. per transit)	Docking Undocking (cas. per transit)	Transiting harbor (cas. per transit)	Open Waters (cas. per mile)	Intracoastal Waterways(cas. per transit)
Collision w/ vessel	5.49×10^{-5}	3.14×10^{-5}	7.20×10^{-5}	6.64×10^{-11}	6.41×10^{-4}
Collision w/ non-vessel	Neg.	7.43×10^{-5}	1.61×10^{-4}	6.94×10^{-11}	1.04×10^{-3}
Explosion/Fire non-cargo	7.87×10^{-7}	4.31×10^{-7}	7.39×10^{-6}	4.84×10^{-11}	4.77×10^{-3}
Grounding	1.29×10^{-5}	7.07×10^{-6}	1.22×10^{-4}	7.71×10^{-11}	6.04×10^{-4}
Foundering capsizing, flooding, heavy weather damage	2.82×10^{-6}	1.56×10^{-6}	2.72×10^{-5}	1.11×10^{-11}	1.83×10^{-4}
Material failure	1.07×10^{-6}	6.09×10^{-7}	1.03×10^{-5}	1.90×10^{-10}	9.54×10^{-5}
Casualty not otherwise classified	4.74×10^{-7}	2.54×10^{-7}	4.50×10^{-6}	1.85×10^{-11}	3.18×10^{-5}
Dangerous environment	Neg.	Neg.	1.25×10^{-6} (CAE)	4.85×10^{-6} (CAE)	4.85×10^{-6} accidents per mile (CAE)

TABLE 3.5

MARINE ACCIDENT RATES BY TYPE AND PHASE OF OPERATION: SHIPS

Phase of Operation / Accident Type	Moored (casualities per transit)	Docking/Undocking (casualities per transit	Transiting harbor (casualties per transit)	Open waters (casualties per mile)
Collision w/ vessel	2.53×10^{-4}	1.44×10^{-4}	3.31×10^{-4}	6.64×10^{-11}
Collison w/ non-vessel	Neg.	2.66×10^{-4}	5.76×10^{-4}	6.94×10^{-11}
Explosion/fire-non-cargo	8.7×10^{-6}	2.2×10^{-6}	8.17×10^{-5}	4.84×10^{-11}
Grounding	5.96×10^{-5}	3.28×10^{-5}	5.63×10^{-4}	7.71×10^{-11}
Foundering capsizing, flooding, heavy weather damage	2.0×10^{-5}	1.11×10^{-5}	1.94×10^{-4}	1.11×10^{-10}
Material failure	1.87×10^{-5}	1.07×10^{-5}	1.80×10^{-5}	1.90×10^{-10}
Casualty not otherwise classified	6.85×10^{-6}	3.76×10^{-6}	6.51×10^{-5}	1.85×10^{-11}
Dangerous Environment	Neg.	Neg.	9.55×10^{-6}	4.85×10^{-6} accidents per mile (CAE)

TABLE 3.6

CAE HANDLING ACCIDENT RATES BY TYPE

Operation (Accident Type)	Fraction of Baseline (Hand Carry) Rate	Accidents Per Unit of Handling
Hand carry (drop)	1.0	1.1×10^{-4}
Forklift (drop or puncture)	1.6	1.8×10^{-4}
Roller track (fall)	0.4	0.4×10^{-4}
Crane (drop or bump)	1.4	1.5×10^{-4}
Container handler (drop or bump)	1.0	1.1×10^{-4}

of three in order to load 3 at once into an aircraft), and 6.9 aircraft or ship loads. Therefore, for each segment the mode determines the number of shipment units used for the sake of valid comparison: highway loading segments use 20.7 loading operations; aircraft unloading segments use 20.7 unloading operations; barge harbor transit segments use 1 harbor transit operation; rail yarding segments use 8.8 yarding operations; highway in-transit segments use a vehicle-mile figure equal to 20.7 x the number of miles in each segment. The combination of shipment units and accident rates determine accident likelihoods.

LIKELIHOOD OF AN INCIDENT OF TYPE J GIVEN AN ACCIDENT OF TYPE I, L(j/i)

The conditional likelihood of an incident given an accident is not dependent upon the segment. For a given material, a given accident type can be expected to produce a given incident type according to a set of likelihoods, no matter what phase of operation is being carried on at the time of the accident. Incident types include spillage (for FCLs only), fire, explosion, and fireball. Tables 3.7 through 3.11 show CAE incident rates (incidents per accident); Table 3.12 shows the FCL values for incidents per shipment associated with the various scenarios mentioned earlier. These incident likelihoods are obtained by multiplying the incident rates times the FCL shipment unit factors discussed above. Thus, the quantity, L(i)s x L(j/i) is comprised of 3 values: incidents per accident, accidents per shipment unit, and shipment units.

For CAEs all combinations of accident types (i) and incident types per accident (L/i) are considered as shown in Tables 3.7 through 3.11. For FCLs only certain combinations of accidents and associated incidents are considered and these are combined into a single value as shown in Table 3.12.

Combinations not listed can be assumed to have a negligible likelihood of occurrence. Sections VII and VIII in Volume II detail how these incident rates and accident-incident scenarios were developed.

TABLE 3.7

CAE HIGHWAY INCIDENT RATES BY ACCIDENT TYPE AND INCIDENT TYPE

Accident Type \ Incident Type	Probability of an incident given the accident type shown		
	Fire	Explosion	Fireball
Collision w/truck	.067	.025	.025
Collision w/auto	.039	.015	.15
Collision w/fixed Object	.024	.009	.009
Collision w/train	.067	.025	.025
Collision w/bus	.051	.019	.019
Collision w/other	.012	.005	.005
Overturn	.024	.009	.009
Ran off road	.016	.006	.006
Jacknife	.016	.006	.006
Separation of units	.012	.005	.005
Dangerous Environments	.067	.025	.025

TABLE 3.8

CAE - RAIL INCIDENT RATES BY ACCIDENT TYPE, INCIDENT TYPE

Accident Type \ Incident Type	Probability of an incident given the accident type shown		
	Fire	Explosion	Fireball
Collision	5.77×10^{-3}	2.19×10^{-3}	2.19×10^{-3}
Derailment	2.81×10^{-3}	1.07×10^{-3}	1.07×10^{-3}
Other	2.11×10^{-3}	8.0×10^{-4}	8.0×10^{-4}
Dangerous Environment	8.30×10^{-2}	3.2×10^{-2}	3.2×10^{-2}

TABLE 3.9

AIR INCIDENT RATES BY ACCIDENT TYPE, AND CAE INCIDENT TYPE

Accident Type \ Incident Type	Probability of an incident given the accident type shown		
	Fire	Explosion	Fireball
Impact-No Fire	.3	.5	.5
Impact-Fire	.4	.5	.5
No Impact-Fire	.2	.6	.6
Dangerous Environment	.067	.025	.025
Inflight			
Landing	.083	.032	.032

TABLE 3.10

CAE MARINE INCIDENT RATES BY ACCIDENT TYPE AND INCIDENT TYPE

Accident Type \ Incident Type	Prob. of an incident given the accident type shown					
	Ship			Barge		
	Fire	Explosion	Fireball	Fire	Explosion	Fireball
Collision with Vessel	.006	.002	.002	.023	.008	.008
Collision with Non-vessel	.003	.001	.001	.006	.002	.002
Explosion/fire Non-cargo	.01	.004	.004	.01	.004	.004
Grounding	.002	.0008	.0008	.023	.008	.008
Foundering, Capsizing, Flooding, Heavy weather	.0006	.0002	.0002	.0006	.0002	.0002
Material Failure	.004	.001	.001	.006	.002	.002
Not Otherwise Classified	.001	.0004	.0004	.002	.0006	.0006
Dangerous Environment	.067	.025	.025	.067	.025	.025

TABLE 3.11

CAE HANDLING INCIDENT RATES BY ACCIDENT TYPE

Operation (unit)	Prob. of an incid. given the accident type shown		
	Fire	Explosion	Fireball
Hand carry (box)	8.33×10^{-6}	3.2×10^{-6}	3.2×10^{-6}
Forklift (pallet)	5.00×10^{-5}	1.9×10^{-5}	1.9×10^{-5}
Roller track (box)	8.33×10^{-6}	3.2×10^{-6}	3.2×10^{-6}
Crane (pallet or container)	5.83×10^{-4}	2.2×10^{-4}	2.2×10^{-4}
Container handler (container)	5.00×10^{-5}	1.9×10^{-5}	1.9×10^{-5}

TABLE 3.12

FCL INCIDENTS PER SHIPMENT, BY SCENARIO TYPE

Scenario No.	Phase	Accident-Incident Scenario	Incident/Shipment Unit
HIGHWAY			
1, 1A	Loading, Unloading	FVC leak - splash or fire	4.12×10^{-6} per truck-load
2, 2A		Liquid phase leak - fire	0.66×10^{-6} per truck-load
3, 3A		Vapor venting - fireball	0.66×10^{-6} per truck-load
4, 4A		Loading warm/unpurged tank - explosion	0.16×10^{-6} per truck-load
5	In-transit	Loss insulation/rapid venting - fireball	1.80×10^{-8} per truck-mile
6		Vehicular accident/12-minute spill - fire	1.80×10^{-8} per truck-mile
7		Vehicular accident/rapid venting - fireball	1.80×10^{-8} per truck-mile
8		Vehicular accident/rapid spill - fire	3.95×10^{-10} per truck-mile
RAIL			
9, 9A	Loading, Unloading	FVC leak - splash or fire	4.12×10^{-6} per carload
10, 10A		Liquid phase leak - fire	0.66×10^{-6} per carload
11, 11A		Loading warm/unpurged tank - explosion	0.16×10^{-6} per carload
12	Origin Terminal	Train accident/28-minute spill - fire	1.40×10^{-6} per carload
13		Train accident/rapid venting - fireball	1.40×10^{-6} per carload

TABLE 3.12 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Incidents/Shipment Unit
14		Train accident/rapid spill - fire	5.50×10^{-8} per carload
15	Destination Terminal	Train accident/28-minute spill - fire	0.70×10^{-6} per carload
16		Train accident/rapid venting - fireball	0.70×10^{-6} per carload
17		Train accident/rapid spill - fire	3.50×10^{-8} per carload
18	Yarding	Train accident/28-minute spill - fire	2.81×10^{-6} per carload
19		Train accident/rapid venting - fireball	2.81×10^{-6} per carload
20		Train accident/rapid spill - fire	1.62×10^{-6} per carload
21	Line Haul	Train accident/28 minute spill - fire	7.02×10^{-9} per car-mile
22		Train accident/rapid venting - fireball	7.02×10^{-9} per car-mile
23		Train accident/rapid spill - fire	7.02×10^{-9} per car-mile
AIR			
24	Loading, Unloading	FCV leak inside aircraft - fire	4.12×10^{-6} per truck
25		Rapid vapor leak inside aircraft - explosion	0.66×10^{-6} per truck
26		Truck accident outside aircraft/two-hour spill - fire	0.05×10^{-4} per truck
27		Rupture trailer inside aircraft - explosion	1.00×10^{-7} per truck

TABLE 3.12 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Incidents/Shipment Unit
28	Static	Aircraft accident/three trailers rupture - fire	2.30×10^{-8} per departure
29	Taxi	Aircraft accident/three trailers rupture - fire	2.68×10^{-8} per departure
30	Take-off	FVC leak/failure to detect - fire	1.00×10^{-8} per departure
31		Aircraft accident/three trailers rupture - fire	4.34×10^{-7} per departure
32	In-flight	FVC leak/failure to detect - fire	1.90×10^{-9} per aircraft mile
33		Aircraft accident/three trailers rupture - fire	4.97×10^{-10} per aircraft mile
34	Landing	FVC leak/failure to detect - fire	1.00×10^{-8} per departure
35		Aircraft accident/three trailers rupture - fire	9.45×10^{-7} per departure
MARINE, ROLL-ON/ ROLL-OFF			
36	Loading, Unloading	FVC leak - fire	0.66×10^{-6} per truck
37		Truck accident/spill - fire fire	0.05×10^{-4} per truck
38		Truck accident/one trailer rupture - fire	1.00×10^{-7} per truck
39	Moored	Vessel accident/leak or spill - fire	2.09×10^{-5} per ship
40		Vessel accident/three trailers rupture - fire	2.32×10^{-6} per ship

TABLE 3.12 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Incidents/Shipment Unit
41	Dock/Undock	Vessel accident/leak or spill - fire	1.19×10^{-5} per ship
42		Vessel accident/three trailers rupture - fire	1.32×10^{-6} per ship
43	Harbor Transit	FVC leak - fire	4.78×10^{-7} per ship
44		Vessel accident/leak or spill - fire	2.74×10^{-5} per ship
45		Vessel accident/three trailers rupture - fire	3.04×10^{-6} per ship
46	Ocean Transit	FVC leak - fire	2.22×10^{-8} per vessel mile
47		Vessel accident/leak or spill - fire	2.35×10^{-12} per vessel mile
48		Vessel accident/three trailers rupture - fire	0.26×10^{-12} per vessel mile
MARINE, BARGE			
49	Loading	FVC leak - fire	1.32×10^{-6} per barge
50		Loading warm/unpurged tank - explosion	0.16×10^{-6} per barge
51	Moored	Vessel accident/leak or spill - fire	7.68×10^{-5} per barge
52		Vessel accident/leak or spill - fire	8.53×10^{-6} per barge
53, 53A	Dock/Undock	Vessel accident/leak or spill - fire	8.78×10^{-6} per barge
54, 54A		Vessel accident/leak or spill - fire	9.75×10^{-7} per barge

TABLE 3.12 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Incidents/Shipment Unit
55	In-transit	FVC leak - fire	6.20×10^{-7} per barge transit of GIWW
56		Vessel accident/leak or spill - fire	2.01×10^{-5} per barge transit
57		Vessel accident/leak or spill - fire	2.24×10^{-6} per barge transit
58	Harbor Transit	FVC leak - fire	6.20×10^{-7} per barge transit
59		Vessel accident/leak or spill - fire	2.01×10^{-5} per barge transit
60		Vessel accident/leak or spill - fire	2.24×10^{-6} per barge transit

The principal difficulty encountered in the development of incident rates has been the scarcity of empirical data from which to derive rates for specific accident-incident scenarios, together with the large number of variables involved in any analytical approach to such derivation. This study assumes that it is preferable to begin with empirical data whenever possible and to disaggregate that data according to engineering analysis. Thus, in most cases, incident rates have been developed by first finding the value of total incidents for all accidents, for each mode from available incident report files. Some breakdowns -- three incident types (spillage, fire, or explosion) and two accident types (vehicular accident or non-vehicular accident) -- are available directly from these data. Further refinements by accident type and for a fourth incident type (fireball) are then made using an analytical approach, as is described in Volume II.

LIKELIHOOD OF SEVERITY LEVEL K GIVEN INCIDENT TYPE J, L(k/j)

Three severity levels are defined for each incident type; these levels are associated with radii of effect and are defined as follows:

- The most severe radius within which all property is damaged or all personnel are injured or killed

- An intermediate radius which is a significant dividing line between lesser and greater effects on personnel or property

- The least severe radius beyond which there is no property damage or effect on personnel.

Thus, the likelihood of severity level k, given incident type j, refers to the chance of injury, fatality, or property damage to those persons or to that property exposed within the radius associated with severity level k, for incident type j. Of course, this chance can be different for different incident types, even within the same severity level. Divisions for severity levels for each incident type were determined according to human and structural tolerance for overpressure and for thermal radiation.

As mentioned previously, the amount of material actually involved in the incident is assumed to be 49.5 tons for all segments of the CAE routes, except for the highway in-transit segments, where the amount is 16.5 tons. However, for FCLs the amount of material involved is not necessarily the same as the total amount of material transported by the carrier in question. For example, only a small amount of material may be involved in a fitting, valve, connector (FVC) leak-pool fire scenario during a highway loading segment.

Figures 3.1 through 3.6 show three severity level curves for each incident type for both personnel and property effects. The amount of material (in TNT equivalence) is used to find the actual radius in feet associated with the severity level for which the percentage of effect is given. Note that this percentage is used as the likelihood L(k/j). FCL amounts are given in Table 3.13 for each accident-incident scenario.

Development of the severity level submodel for both CAEs and FCLs is detailed in Sections VII and VIII of Volume II.

LEVEL OF LOSS ASSOCIATED WITH INCIDENT TYPE J AND SEVERITY LEVEL K FOR SEGMENT S, C(jk)s

The radius associated with each likelihood value given by the submodel L(k/j)s is now read into the loss submodel. This step simply entails the concept that an explosion in a desert has a different loss than the same size explosion in a densely populated terminal area. Figure 3.7 shows the steps involved in arriving at a loss value for a given risk measure radius. Basic demographic characteristics such as population density, employment density, and housing value density are taken from data for the county level, while business property value density is taken from state and national data.

Terminal and mode property value and number of transport-related personnel have been estimated according to: 1) data available for some representative terminal areas, 2) publications for respective modal industries, and 3) judgments of hazardous materials industry experts.

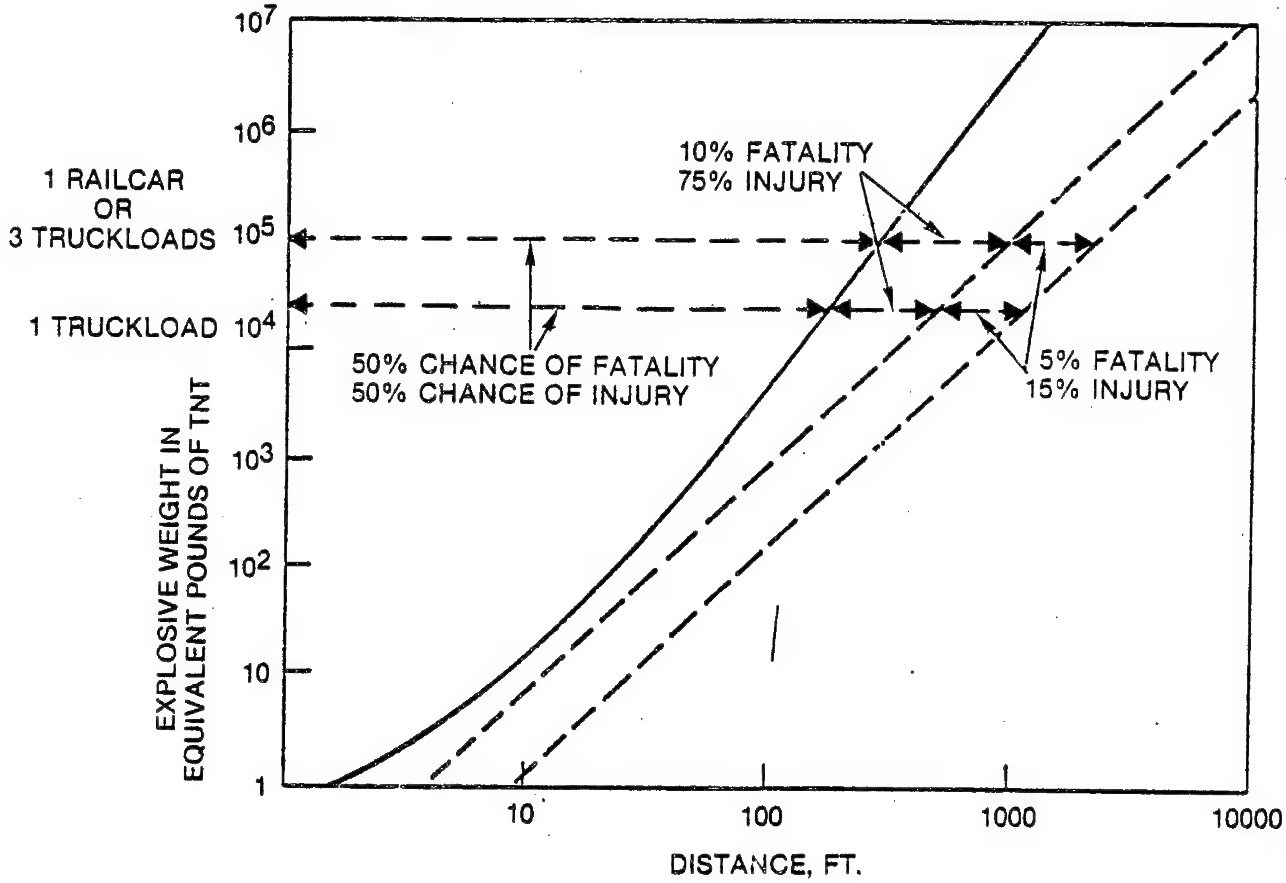


FIGURE 3.1. INJURIES AND FATALITIES FROM EXPLOSIONS: EXPLOSIVE WEIGHT VS. DISTANCE

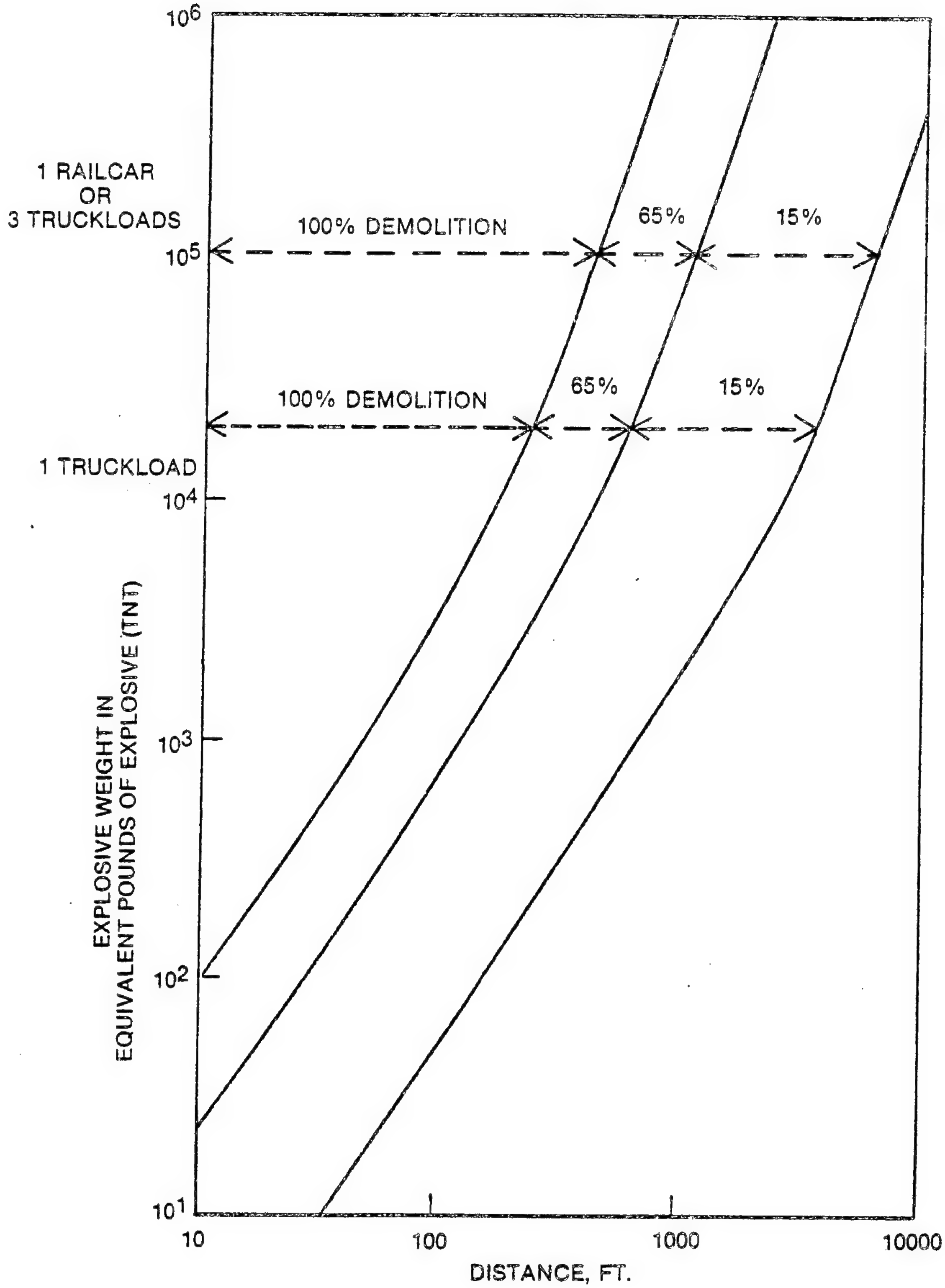


FIGURE 3.2. PROPERTY DAMAGE FROM EXPLOSIONS
EXPLOSION WEIGHT VS. DISTANCES

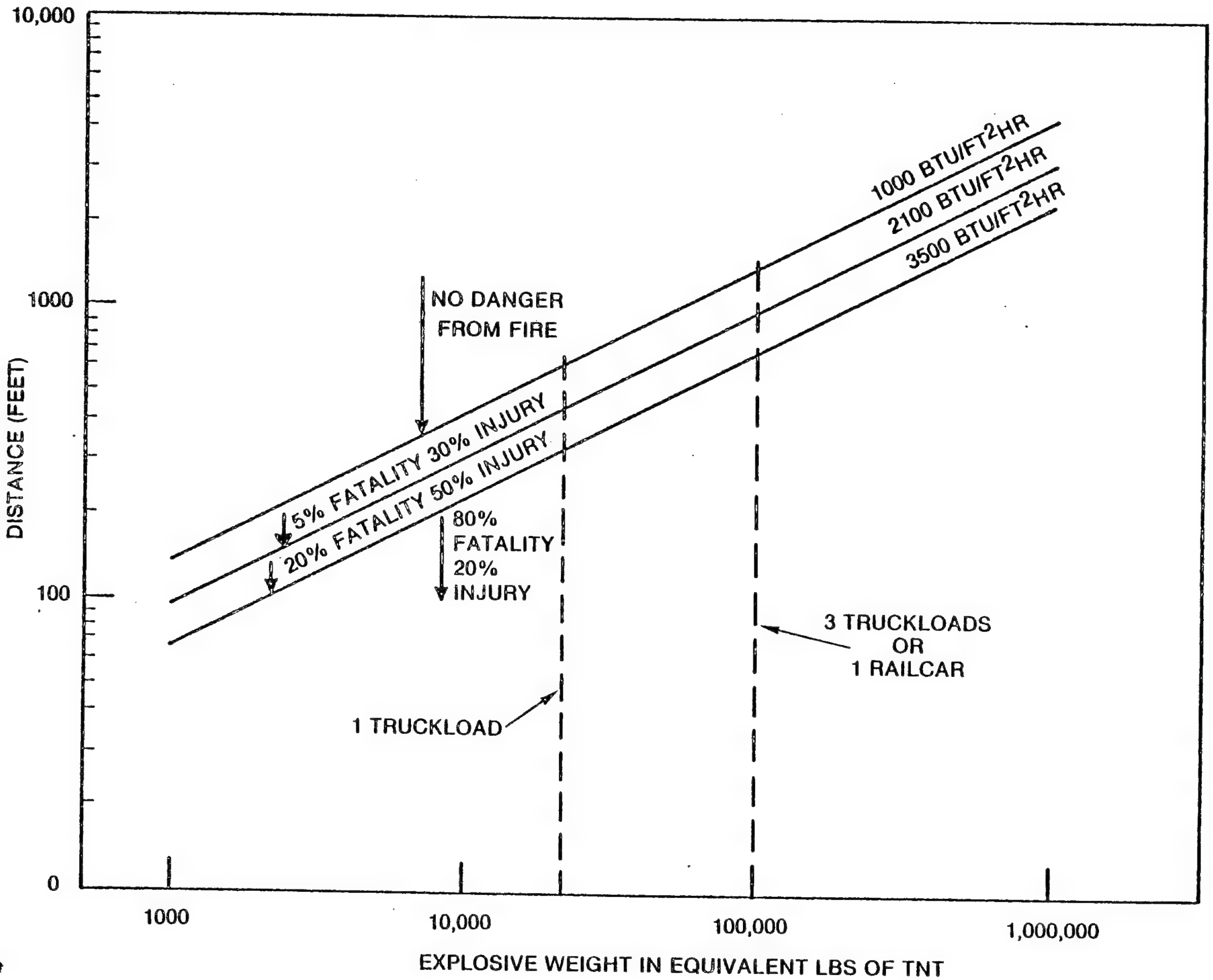


FIGURE 3.3. INJURIES AND FATALITIES FROM FIRE: EXPLOSIVES WEIGHT VS. DISTANCE

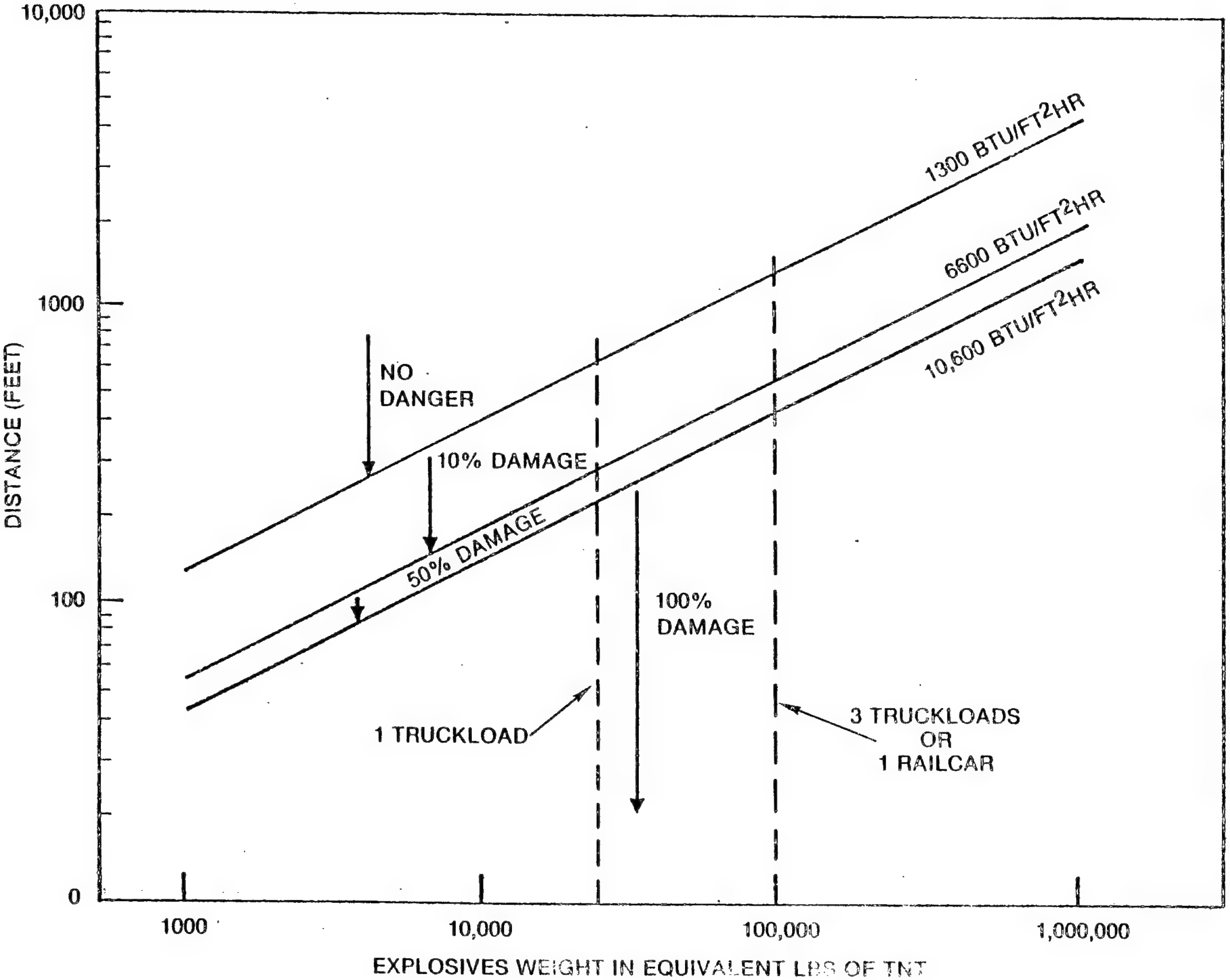


FIGURE 3.4. PROPERTY DAMAGE FROM FIRE: EXPLOSIVES WEIGHT VS. DISTANCE

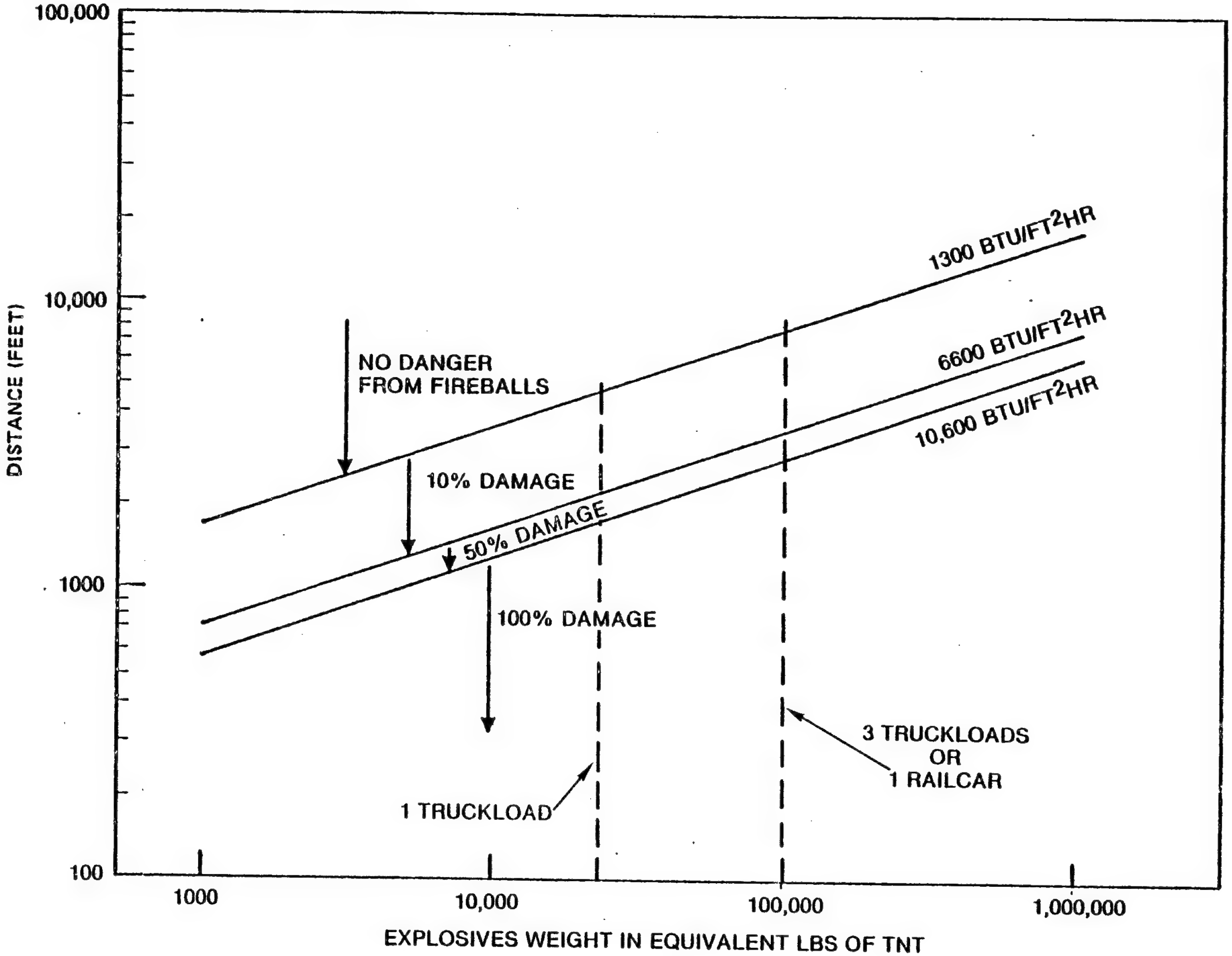


FIGURE 3.5. PROPERTY DAMAGE FROM FIREBALLS: EXPLOSIVE WEIGHT VS. DISTANCE

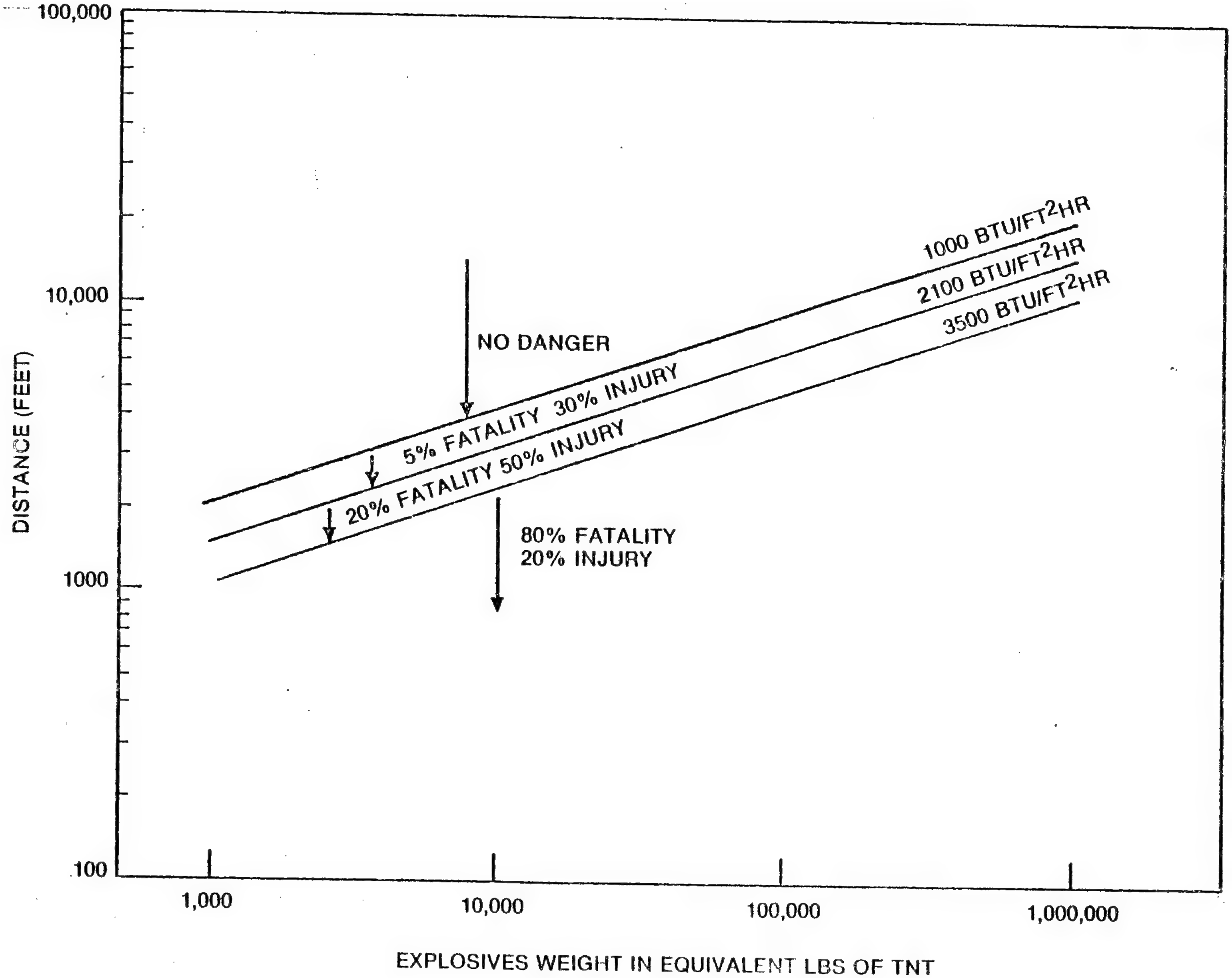


FIGURE 3.6. INJURIES AND FATALITIES FROM FIREBALLS: EXPLOSIVE WEIGHT VS. DISTANCE

TABLE 3.13

AMOUNTS OF FCL MATERIAL INVOLVED IN INCIDENT, BY SCENARIO

Scenario No.	Phase	Accident-Incident Scenario	Amount of LH_2 Involved
HIGHWAY			
1, 1A	Loading, unloading	FVC leak - splash or fire	Only enough for one (1) injury (< 1 qt/min)
2, 2A		Liquid phase leak - fire	4 kg
3, 3A		Vapor venting - fireball	9 kg
4, 4A		Loading warm/unpurged tank/ unpurged tank explosion	3 kg
5	In-transit	Loss insulation/rapid venting - fireball	109 kg
6		Vehicular accident/12 minute spill - fire	375 kg
7		Vehicular accident/rapid venting - fireball	105 kg
8		Vehicular accident/rapid spill - fire	3,240 kg
RAIL			
9, 9A	Loading, unloading	FVC leak - splash or fire	Only enough for one (1) injury (< 1 qt/min)
10, 10A		Liquid phase leak - fire	4 kg
11, 11A		Loading warm/unpurged tank - explosion	9 kg
12	Origin Terminal	Train accident/28 minute spill - fire	375 kg
13		Train accident/rapid venting - fire	150 kg
14		Train accident/rapid spill - fire	7,641 kg

TABLE 3.13 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Amount of LH_2 Involved
15	Destination Terminal	Train accident/28 minute spill - fire	375 kg
16		Train accident/rapid venting - fireball	150 kg
17		Train accident/rapid spill - fire	7,641 kg
18	Yarding	Train accident/28 minute spill - fire	375 kg
19		Train accident/rapid venting - fireball	150 kg
20		Train accident/rapid spill - fire	7,641 kg
21	Line Haul	Train accident/28 minute spill - fire	375 kg
22		Train accident/rapid venting - fireball	150 kg
23		Train accident/rapid spill - fire	7,641 kg
AIR			
24	Loading	FVC leak inside aircraft - fire	Only enough for minor property damages of aircraft, plus two (2) injuries (<1 qt/min)
25		Rapid vapor leak inside aircraft - explosion	10 kg
26		Truck accident outside aircraft/two hour spill - fire	4 kg
27		Rupture trailer inside aircraft - explosion	8,000 kg

TABLE 3.13 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Amount of LH_2 Involved
28	Static	Aircraft accident/three trailers rupture - fire	9,720 kg
29		Aircraft accident/three trailers rupture - fire	9,720 kg
30	Take-off	FVC leak/failure to detect - fire	9,720 kg
31		Aircraft accident/three trailers rupture - fire	9,720 kg
32	In-flight	FVC leak/failure to detect - fire	9,720 kg
33		Aircraft accident/three trailers rupture - fire	9,720 kg
34	Landing	FVC leak/failure to detect - fire	9,720 kg
35		Aircraft accident/three trailers rupture - fire	9,720 kg
<u>MARINE, ROLL-ON/ ROLL-OFF</u>			4 kg
36	Loading, Unloading	FVC leak - fire	4 kg
37		Truck accident/spill - fire	4 kg
38		Truck accident/one trailer rupture - fire	3,240 kg
39	Moored	Vessel accident/leak spill - fire	4 kg
40		Vessel accident/three trailers rupture - fire	9,720 kg

TABLE 3.13 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Amount of LH_2 Involved
41	Dock/Undock	Vessel accident/leak or spill - fire	4 kg
42		Vessel accident/three trailers rupture - fire	9,720 kg
43	Harbor Transit	FVC leak - fire	4 kg
44		Vessel accident/leak or spill - fire	4 kg
45		Vessel accident/three trailers rupture - fire	9,720 kg
46	Ocean Transit	FVC leak - fire	4 kg
47		Vessel accident/leak or spill - fire	4 kg
48		Vessel accident/three trailers rupture - fire	9,720 kg
MARINE, BARGE			
49	Loading	FVC leak - fire	800 kg
50		Loading warm/unpurged tank - explosion	67,500 kg
51	Moored	Vessel accident/leak or spill - fire	800 kg
52		Vessel accident/leak or spill - fire	67,500 kg
53	Dock/Undock	Vessel accident/leak or spill - fire	800 kg
54		Vessel accident/leak or spill - fire	67,500 kg

TABLE 3.13 (cont)

Scenario No.	Phase	Accident-Incident Scenario	Amount of LH_2 Involved
55	In-transit	FVC leak - fire	800 kg
56		Vessel accident/leak or spill - fire	800 kg
57		Vessel accident/leak or spill - fire	67,500 kg
58	Harbor Transit	FVC leak - fire	800 kg
59		Vessel accident/leak or spill - fire	800 kg
60		Vessel accident/leak or spill - fire	67,500 kg

Radius for severity level ______

FOR INCIDENT AT TERMINAL

1. Terminal area within radius ______
2. Terminal personnel exposed (area within radius x personnel density; or number of personnel; from Table 9.1 or 9.2) ______
3. Terminal property exposed (area within radius x property density; or property; from Table 9.1 or 9.2) ______
4. *Crew exposed (crew within radius, from Table 9.3 or 9.4) (count both carriers' personnel if transfer operation) ______
5. *Mode property exposed (property within radius, from Table 9.3 or 9.4) (count both carriers' property if transfer operation) ______
6. **Area outside of terminal within radius ______
7. Persons from public exposed (non-terminal area within radius x average density, from Table 9.6) ______
8. Non-terminal property exposed (non-terminal area within radius x property value density, from Table 9.6) ______

Total persons exposed (lines 2, 4, 7) ______

Total property exposed (lines 3, 5, 8) ______

FOR INCIDENT NOT AT TERMINAL

1. Area within radius ______
2. Right of way area within radius (right of way width x twice radius from Table 9.3 or 9.4) ______
3. Net area within radius (line 1 minus line 2) ______
4. ***Persons from public exposed (net area x average density, from Table 9.6) ______
5. ***Non-mode property exposed (net area x property value density, from Table 9.6) ______
6. Crew exposed (crew within radius, from Table 9.3 or 9.4) ______
7. Mode property exposed (property within radius from Table 9.3 or 9.4) ______

Total persons exposed (line 4, 6) ______

Total property exposed (lines 5, 7) ______

*"O" for crew and property of train if incident is at rail yard; these personnel and property already counted under "terminal personnel exposed" and "terminal property exposed", lines 2 and 3 (assumes crew is scattered during yarding, as are cars of train which eventually leave yard).

**"O" for highway and air terminal incidents; these terminals located with respect to public according to safe separation distances.

***"O" for air no-impact type accident during in-flight phase (assumed to be the only non-terminal air phase), as aircraft whose hazardous cargo detonates or deflagrates while in flight is assumed to be of negligible danger to those on the ground.

FIGURE 3.7. CALCULATION OF PERSONS AND PROPERTY VALUE EXPOSED TO INCIDENT

The size and location of terminals and other facilities associated with each route segment have been determined through consultations with industry distribution experts. Section IX of Volume II contains a complete listing of terminal and non-terminal locations (segments) along each route.

Tables 3.14 through 3.17 show terminal and mode exposures; Tables 3.18 and 3.19 show the kind of information which has been developed in Volume II for locations along each route.

Risk to emergency personnel responding to an accident is computed for a segment only according to the incident likelihood for that segment, i.e., $L(i)sL(j/i)$. Emergency personnel risk (in terms of either injuries or fatalities) is then added to segment population risk (in injuries or fatalities) to obtain total segment risk. Property damage risk is not affected by this aspect of exposure.

Certain assumptions have been made in defining "loss" in terms of people and property value:

- Only direct losses are counted. Indirect losses such as loss of business, cost of evacuation or fire fighting, etc., and clean-up costs are not taken into account; nor are losses from the spreading of secondary fires (these may be controlled by local emergency personnel).

- All persons exposed to an incident are assumed to remain in the locations in which they were found immediately prior to the incident. An explosion, fireball, or spillage incident is considered to be instantaneous and allows no chance for escape; a fire would allow some time to escape but this has already been accounted for in the severity models by the levels of Btu/ft^2 hr associated with percentages of exposed persons injured or killed. No prior evacuation is assumed; this study compares the risks to persons and property which are present without dependence upon local evacuation action.

TABLE 3.14

CAE TERMINAL AREA PERSONNEL AND PROPERTY EXPOSURE

MODE	AREA	RADIUS OF EXPOSED AREA FROM INCIDENT CENTER	PERSONNEL DENSITY OR # PERSONNEL WITHIN AREA (excl. crew)	PROPERTY VALUE DENSITY OR PROPERTY VALUE WITHIN AREA (excl. vehicle in question)
Highway	Loading Dock at Plant*	14'	3	$80,000
	Magazine, Type 1*	40'	4	$145,000 or $245,000 (overseas location)
	Magazine, Type 2*	16'	1	$5,000
Rail	Loading Dock at Plant*	(see highway)		
	Magazine, Type 1 + 2*	(see highway)		
	Yard	2400'	3.3×10^{-6} per sq ft	$4.75 per sq ft
Marine	Individual Terminal Area (Docking/Undocking, moored)	3600'	2.5×10^{-6} per sq ft	$21 per sq ft
	Harbor (Docking/Undocking, moored, transiting harbor)	12,000' or 17,000' (outward from dock)	2.8×10^{-7} per sq ft	$.33 per sq ft
Air	Cargo-only Area (Static)*	170'	10	$200,000
	Airport Runway & Taxi Area (Taxi, Take-off Landing)	3000'	1.6×10^{-5} per sq ft	$8.4 per sq ft

* Special section of larger terminal designated for loading/unloading

TABLE 3.15

FCL TERMINAL AREA EXPOSURE

Terminal Area	Radius	Personnel (Density)	Property (Density)
5-acre plant facility (fenced area)	1100 ft. in one direction only, from truck or rail loading site	.013 per ft. 1 person at loading site	$18,200 per ft.
25-acre non-public area surrounding/including plant facility	600 ft.	N/A	N/A
3-acre storage/distribution facility area	200 ft.	1 person at unloading site	$3.8 per sq. ft.
Marine barge-loading terminal area at plant	2500 ft., in one direction only, from barge loading site	.002 persons per ft. (includes person at loading site)	$16,000 per ft.
Marine roll-on/roll-off terminal area	3600 ft.	4×10^{-6} persons per sq. ft.	$21 per sq. ft.
Harbor area	12,000 ft.	2.8×10^{-7} persons per sq. ft.	$0.33 per sq. ft.
Rail yard	2400 ft.	3.3×10^{-6} persons per sq. ft.	$4.75 per sq. ft.
Airport cargo-only area	170 ft.	10	$200,000
Airport runway area	3000 ft.	1.6×10^{-5} persons per sq. ft.	$8.4 per sq. ft.

TABLE 3.16

CAE MODE PERSONNEL AND PROPERTY EXPOSURE

MODE	RADIUS	# CREW	$PROPERTY	RIGHT OF WAY TOTAL WIDTH
Highway In-Transit Phase	40'	2	$60,000	400'
Highway, Loading and Unloading Phase	150'	6	$180,000	N/A
Rail *	2000'	.001 per/ft.	$1800 per/ft.	65'
Marine, Ship	250'	26	$35 million	N/A
Marine, Barge & Tug unit (non-lightering)	250'	4	$1.7 million	N/A
Lightering	250'	4	$2.6 million	N/A
Air	100'	3	$4.7 million	N/A

* For loading or unloading at plant or magazine, use "0" for number of crew, "$50,000" for property dollars.

TABLE 3.17

FCL MODE PERSONNEL AND PROPERTY EXPOSURE

Mode	Radius	Crew	Property	Right of Way (Total Width)
Highway	40 ft.	2	$250,000	400 ft.
Rail	2,000 ft.	.001 persons per ft.	$1,800 per ft.	65 ft.
Loading/unloading segment only	N/A	0	$600,000	N/A
Marine, barge and tug unit	200 to 325 ft.	4	$4.4 million	N/A
Loading segment only	N/A	0	$3 million	N/A
Marine, roll-on/roll-off ship	500 ft.	.025 persons per ft.	$61,200 per ft.	N/A
Air	100 ft.	3	$4.7 million	N/A

TABLE 3.18

PERSONNEL AND PROPERTY VALUE EXPOSURE: CAE, BESSEMER, ALABAMA, TO MINDY DOCKS, PANAMA, NON-AIR ALTERNATIVE

State	County	Average Personnel Density (persons per square mile)	Property Value Density (million dollars per square mile)
Alabama	Jefferson	601	2.82
	Shelby	58	.36
	Chilton	36	.31
	Autauga	45	.40
	Elmore	58	.44
	Montgomery	232	1.41
	Lowndes	17	.26
	Butler	27	.29
	Conecuh	18	.26
	Escambia	37	.32
	Baldwin	39	.37
	Mobile	269	1.28
Mississippi	Jackson	148	.68
	Harrison	235	1.18
Gulf of Mexico		0	0
Caribbean Sea		0	0
Canal Zone		122	.54

TABLE 3.19

CAE, Bessemer, Alabama, to Mindy Docks, Panama:
Non-air Alternative

Modes: Rail - Bessemer to Gulfport, Mississippi
Marine - Gulfport to Mindy Docks

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
1	Rail, Loading (1980 boxes by roller track), plant loading dock		Jefferson, Ala.
2	Rail, Origin Terminal Operations, plant loading dock		Jefferson
3		Rail, line haul, 5 miles	Jefferson
4	Rail, Yarding (Bessemer)		Jefferson
5		Rail, line haul,16 miles	Jefferson
6	Rail, Yarding (Birmingham)		Jefferson
7		Rail, line haul, 4 miles	Jefferson
8		Rail, line haul,25 miles	Shelby
9		42 "	Chilton
10		4 "	Autauga
11		12 "	Elmore
12		23 "	Montgomery
13		15 "	Lowndes
14		41 "	Butler
15		21 "	Conecuh
16		44 "	Escambia
17		36 "	Baldwin
18		29 "	Mobile
19		34 "	Jackson, Miss.
20		8 "	Harrison
21	Rail, Yarding (Gulfport)		Harrison

TABLE 3.19 (Con't)

Modes: Rail - Bessemer to Gulfport, Mississippi
Marine - Gulfport to Mindy Docks

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
22		Rail, line haul, 5 miles	Harrison
23	Rail, Destination Terminal operations (individual marine terminal at Port of Gulfport)		Harrison
24	Rail, Unloading (1980 boxes by hand onto pier into pallets) marine terminal		Harrison
25	Marine, Loading (55 netted parrets onto Ship by crane), marine terminal		Harrison
26	Marine (Ship), Moored, Marine Terminal		Harrison
27	Marine Undocking, Marine terminal		
28	Marine, Harbor transit, Gulfport harbor		
29		Marine, open ocean transit (Gulf of Mexico & Caribbean Sea), 1500 miles	n/a
30	Marine, Harbor transit, Christobal harbor		Canal Zone
31	Marine Docking, Mindy Docks Marine terminal at Christobal harbor		Canal Zone
32	Marine, Moored, Marine terminal		Canal Zone

TABLE 3.19 (Con't)

Modes: Rail - Bessemer to Gulfport, Mississippi
Marine - Gulfport to Mindy Docks

Segment	Phase of Operation: Terminal	Phase of Operation: Non-Terminal	County
33	Marine, Unloading, Marine terminal (55 pallets by crane; 1980 boxes by hand from disassembled pallets onto narrow gauge rail carts		Canal Zone
34	Handling, Loading (1980 boxes by hand from disassembled pallets onto narrow gauge rail carts), Marine terminal.		Canal Zone
35	Handling, Unloading (1980 boxes by hand from carts), at magazine, type 1.		Canal Zone
	*Assumes no risk for transfer of carts along short track between pier and magazine (magazine is a safe-separation distance away only)		

- Exposure is calcuated as if all personnel were standing in the open and all property were vulnerable.

- The cost of the hazardous material in the shipment under consideration is not counted as property value exposed.

It should also be noted that, as an intermediate step in calculating segment loss, specific "exposure modules" were developed for each type of segment where exposure levels would differ. However, these modules are not included in this report, since they are derived directly from 1) the terminal and mode exposure tables already given and from 2) the specific radii associated with each severity level and material amount which is applicable to the segment type in question. Instead, Figure 3.7 shows the general formula for deriving the specific "exposure module" values of C(jk)s. Of course, certain assumptions as to when crew personnel and mode property can be expected to be nearby, such as during transfer operations, are still necessary. These are explained by way of example in Section IV.

AGGREGATION OF SEGMENT RISKS

The expected value risk model which has been described in this section is illustrated in Section IV of this volume for a single segment. The comparison of risks by mode is achieved by aggregating the risks for all segments in a route and comparing this value to the aggregated value of risk for the alternative route. Two alternative methods were considered for performing this aggregation across segments:

(a) One method treats the likelihoods of incident occurrence in different segments as if they were completely independent of the likelihoods in the preceding segments. Thus, risks associated with each segment are simply added together to obtain the risk associated with the entire route.

(b) An alternative method takes into account the fact that likelihoods from preceding segments (i.e., "downstream" likelihoods) are reduced by "upstream" likelihoods. Thus, the

likelihood of an incident occurring in a given segment is really the product of the likelihood of an incident not occurring in all previous segments and the independent likelihood of an incident occurring in that segment. Considering the very low likelihoods of incident occurrence, this product will be very close to the value of the independent likelihood for that segment.

The first method was considered to be sufficiently accurate and was preferred for manual computation from the standpoint of simplicity. The second was considered desirable where computerized aggregation was used. After a detailed analysis of the factors involved, computerization was elected as the means for calculating CAE risks but not for FCL risks. Therefore, risks are aggregated for an entire FCL route by addition of the risks for all of the separate segments comprising that route; CAE route segment risks are aggregated as described under method (b) above. For example, the Class A explosives route from Bessemer, Alabama to Mindy Docks, Panama is evaluated by comparing the fatalities, injuries, and property damage expected for the shipment of 49.5 tons of dynamite by rail to Gulfport, by ship to Panama, and by a handling procedure to final destination near the dock area, with the fatalities, injuries, and property damage expected for the shipment of the same amount of dynamite by truck to an Alabama airport, by air to Panama, and by truck to the final destination. The segments involved in the Bessemer to Panama non-air alternative route are described in Tables 3.18 and 3.19, given previously in this section. Actual computations for one of the three risk measures -- fatalities -- are described in detail in Section IV (Volume I) for both alternative routes. These computations include the aggregation of fatality risks over all segments for each route and thereby allows comparison of fatality risk for the rail-ship route with fatality risk for the truck-air-truck alternative route.

Section V (Volume I) presents the results of the model and the aggregated risks for all twelve pairs of alternative routes (24 total routes) associated with the twelve stipulated origin-destination pairs.

SALIENT FEATURES OF THE MODEL

The approach to risk assessment used in this study involves a conventional analytic model -- the expected value model. However, integration of this model into the entire risk assessment process has involved several refinements to the conventional approach and also some entirely new concepts. The following paragraphs point out the more significant of these refinements and concepts plus some possibilities for developing the methodology for broader applications.

Use of Dangerous Environment Concept

For the purposes of risk calculations in this study, the progression from accident to incident to severity radius to loss requires that all hazardous material incidents originate as accidents. In fact, however, some loss generating events do not result from carrier accidents, but instead from activities such as intense vibration encountered by a vehicle during its normal course of operation. As such, certain "normal environments" are capable of producing a hazardous material release (i.e., incident) without a carrier accident occurring. Because there is no direct way of counting these normal environments that could produce an incident, the approach taken herein counts all incidents that do not stem from a handling or vehicular accident as "dangerous environment" incidents. A detailed review of historical incident reports, together with data from several recent hazardous materials incidents which were indeed caused simply by dangerous environments, indicates the importance of this factor.

Use of a Combined Empirical-Analytical Approach

The likelihood and cost inputs to the four submodels were not, in certain cases, directly available from accident or incident data. The approach in these cases was to use empirical data whenever possible, substituting engineering analysis for any data not available from recorded experience. In all cases aggregate data were obtained empirically; disaggregations were then sometimes done analytically. This meant that all likelihoods or costs, whether empirically or analytically derived, were

originally based on experience data and were therefore felt to be the most reasonable estimates possible. Thus, this approach maintains the ratio of relative risks among the different modes, which is the object of the study. A good example of the application of this technique is the calculation of the in-flight accident rate due to dangerous environments. The empirically derived highway mode "dangerous environment" rate was used as a base, then an engineering analysis was used to compare highway and air normal environments in terms of specific parameters. Thus, the dangerous environment rate derived for in-flight operations was the result of a combination of empirical and analytical methods.

Another example of analytical disaggregation of empirical data is in the derivation of highway incident rates by accident type. Here again, the overall highway incident rate was taken from documented events; specific rates associated with each accident type were broken out according to analysis of impacts and other parameters.

Use of Routes for Comparison of Modes

An important assumption of this study was that it would not be meaningful to assess the risk of transporting hazardous material in the air mode without assessing the total risk involved in each of the other modal operations which shipment by air necessitates. The air risk is always computed with respect to a certain route and a combination of modes covering an origin-destination pair. This air shipment route is compared with another entire route which does not involve air shipment. For this reason, the values for risk found in the calculations of Section V should not be taken to represent the risks associated exclusively with the modes involved; nor should they be used to compare explicitly the relative safety of one mode with another. Risks depend on the phase of operation and geographical location involved in each segment, and on the frequency of each segment type traversed within each route. The risk for a given segment could be several orders of magnitude different from the risk for another segment, even where the same mode is involved for each.

This is not to suggest that it is impractical to make responsible decisions concerning air transport of hazardous materials without examining every segment of a proposed route and its non-air alternative in minute detail. Indeed, since the twelve origin-destination pairs chosen for analysis in this study are assumed to be representative of expected shipping patterns, it is reasonable to give the comparisons drawn from them considerable weight when analyzing the risks involved in other proposed hazardous materials shipments.

On the other hand, it is essential that the differences between a route analyzed in this study and another proposed route be delineated carefully so that all important risk factors are considered. A thorough understanding of the factors influencing the risks in each segment along a route is necessary for making judgments concerning the relative safety of a given mode.

Use of Origin-Destination Risk Values

The most useful output of this study is the model itself, along with the model input data (in the form of tables and curves) and the techniques for selecting the data and performing the calculation. With these tools, risks can be quantified for any route that may be of concern to the Materials Transportation Bureau. The twelve origin-destination pairs are themselves very useful, primarily as illustrations of the many factors which affect risk. These factors are discussed at the conclusion of Section IV (sample calculations) and indicate how the origin-destination pairs provide a perspective necessary for assessing air transport hazardous materials risks.

Use of Single Risk Values and Possible Construction of Risk Profiles

Instead o using the model to arrive at a single risk value (for fatalities or injuries or property damage) for each route alternative, it is possible to apply the model in constructing a risk profile curve for each alternative. Such a construction would be based on the severity level submodel approach, showing the likelihood of producing F or more fatalities, injuries, or damage for many separate values of F. That is, the (unconditional) likelihood of arriving at a certain severity level (accident likelihood x incident likelihood given accident x severity level likelihood

given incident) is associated, via the model, with the loss expected from that severity level. It may be useful, for example, to be able to find the likelihood of a certain level of injuries along the route, in which some significant injury-level steps may have been hidden. However, the construction of such complete profiles was considered to be beyond the scope of this study. Some samples of partial profiles are given in Section V.

Use of Worst Case Approach

While the worst case approach is certainly not a new concept in risk assessment, its use in this study has been particularly selective and carefully considered. Where it has been possible to determine a statistically expected situation which is different from the worst case, that option has been taken. This is particularly true of the analyses relating to FCL accident-incident scenarios in Volume II, Section VIII. Where the worst case approach has been incorporated, such as in the modeling of numbers of persons exposed, this assumption has been noted. (See Volume II, Section IX -- discussion of all persons exposed assumed to be unprotected.)

Use of the Modular Approach to Risk Assessment

Two types of modules have been used in this study: a) the segments and material amounts used to define a route, and b) the submodels used to compute likelihood and loss level values along those segments. Sensitivity of overall risk to route changes, modal safety improvements, or material handling or packaging breakthroughs can be found by simply adjusting the appropriate modules. The detailed information given in Volume II is easily adaptable to substitution of more current data. It is with this possibility in mind, for example, that empirically derived overall highway incident rates have been disaggregated by accident type. Incident rates for certain highway accident types might be assumed to be sensitive to better packaging, while incident rates for the other highway accident types may not be. With this disaggregation, the incident rate may be adjusted without waiting for several years' records of empirical data.

Use of Risk Factors to Guide Level of Detail in Analyses

A considerable effort has been expended on the analysis of modal accident data in order to define those factors which significantly affect risk. Results have indicated that different modes must be treated at different levels of detail. For example, air mode accident rates by type can be directly related to specific phases of operation, such as take-off, in-flight, or landing. However, rail mode accident rates by type for each phase must be produced from combinations of accident rates for specific railroad procedures (risk factors) such as switching, coupling, etc., which make up each phase. Furthermore, this level of detail is useful as input for accident rate disaggregation for the rail and marine modes (because of the risk factor differences in each cause) but is not necessary for the air or highway mode.

Analytical Approach to Loss Level Modeling

It has been found in this study that empirical data is generally preferable to engineering analysis. However, in the case of the loss level submodel, C(jk)s, the reverse is true. The use of empirical loss data covering past hazardous materials accidents can lead to excessive error because of the low probability/high cost nature of some incidents. Therefore, this study has chosen to use an analytical matching of severity levels (footprints) with county level personnel and property value densities, or with terminal area densities, depending on segment type. This allows for more accuracy in determining sensitivity of risk to local demography associated with alternative routings.

Use of County-Level Census Data

Route-dependent segments are developed by applying county-level data to modular types of operations and facilities. The use of county data to correspond with discrete segment risks is an important element of the overall study. It allows potentially vast amounts of input data to be more readily managed, even though it sacrifices the accuracy that might be achieved by subdividing counties into such density patterns as urban, suburban, and rural.

IV. IMPLEMENTATION OF THE EXPECTED VALUE MODEL AND COMPARISON OF RISKS:

CLASS A EXPLOSIVES, BESSEMER, ALABAMA, TO MINDY DOCKS, PANAMA; AND, FLAMMABLE CRYOGENIC LIQUIDS, ONTARIO, CALIFORNIA, TO McCOOK, ILLINOIS

DESCRIPTIONS AND CALCULATIONS

This section gives two examples of the implementation of the risk assessment methodology described in the previous section: one for Class A explosives and one for flammable cryogenic liquids. Risks are assessed and compared for the air and non-air alternatives for shipment of 49.5 tons of dynamite from Bessemer, Alabama, to Mindy Docks, Panama, and for shipment of 250,000 gallons of LH_2 from Ontario, California, to McCook, Illinois. Tables 4.1 through 4.4 show the segments involved in each of the four alternative routes.

In addition, the factors influencing the risk values in a few segments are highlighted to more fully illustrate the sensitivity of risk to route characteristics, as well as to provide a better perspective for the quantitative results of the assessment of the remaining routes which are set forth in Section V.

For the purposes of these examples, only one risk measure -- that of fatalities -- is considered.

TABLE 4.1

CAE, Bessemer, Alabama, to Mindy Docks, Panama:
Non-air Alternative

Modes: Rail - Bessemer to Gulfport, Mississippi
Marine - Gulfport to Mindy Docks

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
1	Rail, Loading (1980 boxes by roller track), plant loading dock		Jefferson, Ala.
2	Rail, Origin Terminal Operations, plant loading dock		Jefferson
3		Rail, line haul, 5 miles	Jefferson
4	Rail, Yarding (Bessemer)		Jefferson
5		Rail, line haul,16 miles	Jefferson
6	Rail, Yarding (Birmingham)		Jefferson
7		Rail, line haul, 4 miles	Jefferson
8		Rail, line haul,25 miles	Shelby
9		42 "	Chilton
10		4 "	Autauga
11		12 "	Elmore
12		23 "	Montgomery
13		15 "	Lowndes
14		41 "	Butler
15		21 "	Conecuh
16		44 "	Escambia
17		36 "	Baldwin
18		29 "	Mobile
19		34 "	Jackson, Miss.
20		8 "	Harrison
21	Rail, Yarding (Gulfport)		Harrison

TABLE 4.1 (Con't)

Modes: Rail - Bessemer to Gulfport, Mississippi
Marine - Gulfport to Mindy Docks

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
22		Rail, line haul, 5 miles	Harrison
23	Rail, Destination Terminal operations (individual marine terminal at Port of Gulfport)		Harrison
24	Rail, Unloading (1980 boxes by hand onto pier into pallets), marine terminal		Harrison
25	Marine, Loading (55 netted pallets onto Ship by crane), marine terminal		Harrison
26	Marine (Ship), Moored, Marine Terminal		Harrison
27	Marine Undocking, Marine terminal		
28	Marine, Harbor transit, Gulfport harbor		
29		Marine, open ocean transit (Gulf of Mexico & Caribbean Sea), 1500 miles	n/a
30	Marine, Harbor transit, Christobal harbor		Canal Zone
31	Marine Docking, Mindy Docks Marine terminal at Christobal harbor		Canal Zone
32	Marine, Moored, Marine terminal		Canal Zone

TABLE 4.1 (Con't)

Modes: Rail - Bessemer to Gulfport, Mississippi
Marine - Gulfport to Mindy Docks

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
33	Marine, Unloading, Marine terminal (55 pallets by crane; 1980 boxes by hand from disassembled pallets onto narrow gauge rail carts)		Canal Zone
34	Handling, Loading (1980 boxes by hand from dis-assembled pallets onto narrow gauge rail carts), Marine Terminal		Canal Zone
35*	Handling, Unloading (1980 boxes by hand from carts), at magazine, type 1.		Canal Zone
	*Assumes no risk for transfer of carts along short track between pier and magazine (magazine is a safe-separation distance away only)		

TABLE 4.2

CAE, Bessemer, Alabama, to Mindy Docks, Panama:
Air Alternative

Modes: Highway - Bessemer to Huntsville, Alabama
Air - Huntsville to Balboa, Panama
Highway - Balboa to Mindy Docks

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
1	Highway, Loading (1980 boxes for 3 trucks by roller track), loading dock at plant		Jefferson
2		Highway, transit, 34 miles	Jefferson
3		38 "	Blount
4		14 "	Marshall
5		8 "	Morgan
6		10 "	Madison
7	Highway, unloading (1980 boxes by hand into pallets), cargo only area at Huntsville airport		Madison
8	Air, loading (55 pallets by forklift) cargo-only area		Madison
9	Air, Static, cargo - only area		Madison
10	Air, taxi, runway area Huntsville airport		Madison
11	Air, take-off, runway area at Huntsville airport		Madison
12		Air, in-flight 10 miles	Madison
13		10 "	Morgan
14		12 "	Marshall
15		36 "	Blount
16		22 "	St. Clair
17		38 "	Shelby

TABLE 4.2 (Con't)

Modes: Highway - Bessemer to Huntsville, Alabama
Air - Huntsville to Balboa, Panama
Highway - Balboa to Mindy Docks

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
18		Air, in-flight 10 miles	Talladega
19		26 "	Coosa
20		18 "	Elinore
21		144 "	Montgomery
22		32 "	Crenshaw
23		24 "	Coffee
24		14 "	Geneva
25		16 "	Holmes, Florida
26		18 "	Walton
27		6 "	Bay
28		1500"	(Gulf of Mexico & Caribbean Sea)
29		48 "	Panama, Non-Canal Zone
30	Air, Landing, Runway		Panama (Non-Canal Zone)
31	Air, taxi, runway area, Balboa Airport		Panama
32	Air, static, cargo-only area		Panama
33	Air, unloading (55 pallets by forklift), cargo-only area		Panama
34	Highway, loading (1980 boxes for 3 trucks by hand), cargo-only area		Panama
35		Highway, transit, 34 miles	Canal Zone

TABLE 4.2 (Con't)

Modes:	Highway - Bessemer to Huntsville, Alabama Air - Huntsville to Balboa, Panama Highway - Balboa to Mindy Docks		
Segment	Phase of Operation		County
	Terminal	Non-Terminal	
36	Highway, Unloading (1980 boxes by Hand), Magazine, Type 1, at Mindy Docks		Canal Zone

TABLE 4.3

FCL, Ontario, California, to McCook, Illinois:
Non-Air Alternative

Modes:

Rail--Ontario to McCook

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
1	Rail, loading (28,300-gallon tank car), rail loading site at plant, Ontario facility		San Bernardino
2	Rail, origin terminal operations, rail loading site		San Bernardino
3		Rail, line haul, 191 miles	San Bernardino
4	Rail, yarding, Colton Yard.		San Bernardino
5		Rail, line haul, 57 miles	Mojave, Arizona
6		43 "	Yavapai
7		78 "	Coconino
8		43 "	Navajo
9		38 "	Apache
10		34 "	McKinley, N.Mex.
11		109 "	Valencia
12		65 "	Torrence
13		22 "	Guadeloupe
14		50 "	De Baca
15		12 "	Roosevelt
16		37 "	Curry
17		36 "	Parmer, Texas
18		27 "	Deaf Smith
19		24 "	Randall
20		15 "	Potter
21		36 "	Carson
22		36 "	Roberts

TABLE 4.3 (Cont'd)

FCL, Ontario, California, to McCook, Illinois:
Non-Air Alternative

Modes:			
Rail--Ontario to McCook			
Segment	Phase of Operation		County
	Terminal	Non-Terminal	
23		Rail, line haul 33 miles	Hemphill
24		" " 29 "	Ellis, Oklahoma
25		41 "	Woodward
26		31 "	Woods
27		16 "	Barber, Kansas
28		30 "	Harper
29		10 "	Kingman
30		46 "	Sedgwick
31		4 "	Harvey
32		10 "	Butler
33		20 "	Marion
34		28 "	Chase
35		22 "	Lyon
36		26 "	Osage
37		26 "	Douglas
38		20 "	Johnson
39		4 "	Wyandotte
40		22 "	Clay, Missouri
41		24 "	Ray
42		22 "	Carroll
43		6 "	Livingston
44		6 "	Chariton
45		16 "	Linn
46		28 "	Macon
47		24 "	Knox

TABLE 4.3 (Cont'd)

FCL, Ontario, California, to McCook, Illinois:
Non-Air Alternative

Modes:

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
48		Rail, line haul 8 miles	Lewis
49		18 "	Clark
50		34 "	Hancock, Illinois
51		28 "	Warren
52		30 "	Knox
53		22 "	Stark
54		8 "	Marshall
55		22 "	Putnam
56		36 "	La Salle
57		20 "	Kendall
58		14 "	Will
59		17 "	Cook
60	Rail, yarding, Corwith yard		Cook
61		Rail, line haul 6 miles	Cook
62	Rail, destination terminal operations, railloading site at McCook-storage facility		Cook
63	Rail, unloading (28,300-gallon tank car), rail unloading site		Cook

TABLE 4.4

FCL, Ontario, California, to McCook, Illinois:
Air Alternative

Modes:

Highway--Ontario to Palm Springs, California
Air--Palm Springs to Decatur, Illinois
Highway--Decatur to McCook

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
1	Highway, loading (12,160-gallon tank truck), truck loading site at plant, Ontario facility		San Bernardino
2		Highway, transit, 37 miles	San Bernardino
3		37 "	Riverside
4	Air, loading (3 trucks into cargo compartment of cargo aircraft), cargo-only area, Palm Springs Airport		Riverside
5	Air, static, cargo only area		Riverside
6	Air, taxi, runway area		Riverside
7	Air, take-off, runway area		Riverside
8		Air, in-flight, 22 miles	Riverside
9		99 "	San Bernardino
10		57 "	Mojave, Arizona
11		116 "	Coconino
12		38 "	Navajo
13		46 "	Apache
14		76 "	San Juan, N.M.
15		35 "	Rio Arriba
16		20 "	Aachuleta, Colo.
17		51 "	Conejos
18		31 "	Costilla
19		33 "	Huerfano
20		26 "	Las Animas
21		37 "	Otero

TABLE 4.4 (Cont'd)

FCL, Ontario, California, to McCook, Illinois:
Air Alternative

Modes:

Highway--Ontario to Palm Springs, California
Air--Palm Springs to Decatur, Illinois
Highway--Decatur to McCook

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
22		Air, in-flight, 37 miles	Bent
23		37 "	Prowers
24		26 "	Hamilton, Kansas
25		26 "	Wichita
26		24 "	Scott
27		24 "	Lane
28		36 "	Ness
29		28 "	Rush
30		28 "	Barton
31		36 "	Ellsworth
32		30 "	Saline
33		26 "	Dickinson
34		20 "	Morris
35		30 "	Wabaunsee
36		22 "	Shawnee
37		34 "	Douglas
38		18 "	Leavenworth
39		16 "	Wyandotte
40		24 "	Jackson, Missouri
41		22 "	Ray
42		24 "	Carroll
43		12 "	Saline
44		18 "	Chariton
45		20 "	Randolph
46		34 "	Monroe

TABLE 4.4. (Cont'd)

FCL, Ontario, California to McCook, Illinois:
Air Alternative

Modes:

Highway--Ontario to Palm Springs, California
Air--Palm Springs to Decatur, Illinois
Highway--Decatur to McCook

Segment	Phase of Operation		County
	Terminal	Non-Terminal	
47		Air, in-flight, 26 miles	Ralls
48		29 "	Pike, Illinois
49		14 "	Scott
50		22 "	Morgan
51		40 "	Sangamon
52		18 "	Macon
53	Air, landing, runway area, Decatur airport		Macon
54	Air, taxi, runway area		Macon
55	Air, static, cargo-only area		Macon
56	Air, unloading (3 trucks out of cargo compartment), cargo-only area		Macon
57		Highway, transit, 9 miles	Macon
58		15 "	DeWitt
59		36 "	McLean
60		36 "	Livingston
61		15 "	Grundy
62		36 "	Will
63		7 "	DuPage
64		9 "	Cook
65	Highway, unloading (12,160-gallon tank truck) truck unloading site at McCook storage facility		Cook

Tables 4.5 through 4.8 show the steps involved in computing fatality risk for each segment of the four alternative routes.

The value for L(i)sL(j/i) is found by applying the number of shipment units found in the second column of these tables to the accident rate and incident rate found in the appropriate table in Section III. That is:

1) A CAE handling accident likelihood (L(i)s) is found according to the expression $1-(1-x)^n$, for x = accident rate, n = shipment units; this value is then multiplied by the incident rate.

2) A CAE in-transit accident likelihood is found by multiplying the accident rate by the mileage and then by the number of vehicles; this value is then multiplied by the incident rate.

3) A CAE terminal operations accident likelihood is the same as the accident rate; this value is then multiplied by the incident rate.

4) An FCL in-transit incident likelihood (L(i)sL(j/i)) is found by multiplying the incident rate by the mileage and then by the equivalency factor for that mode (as explained in Section III).

5) An FCL terminal operations or handling incident likelihood is found by multiplying the incident rate by the equivalency factor for that mode.

The values for L(k/j) can be taken directly from the severity level curves given in Section III. The calculation of the value for C(jk)s, however, requires an understanding of the physical configuration of the areas where the incidents occur. Specifically, it is necessary to know if there will be terminal personnel involved, if the public will be involved, or both. Terminal personnel may include personnel from more than one density type of terminal area, such as at the marine and air terminal areas. Mode personnel

TABLE 4.5

FATALITY RISK CALCULATION FOR CAE, BESSEMER TO PANAMA (NON-AIR)

Segment	Shipment Units	Exposure: Terminal	Exposure: Mode	Exposure: Public	$\Sigma L(i)sL(j/i)L(k/j)C(jk)s$	Emergency Personnel $(\Sigma L(i)SL(j/i))\cdot .0001$	Total Risk
1	1980 boxes	Loading Dock personnel	No train crew	None	2.47×10^{-6}	1.12×10^{-10}	2.47×10^{-6}
2	1 car	Loading Dock personnel	Train Crew in one direction	None	1.38×10^{-6}	5.20×10^{-11}	1.38×10^{-6}
3	5 miles	None	Train crew in two directions	Within radius of incident, less right of way area	9.36×10^{-6}	1.32×10^{-9}	9.36×10^{-6}
4	1 car	Yard personnel	No crew	Outside of yard radius	2.26×10^{-5}	6.90×10^{-9}	2.26×10^{-5}
5	16 miles	None	Train crew, 2 directions	Within radius of incident, less R.O.W. area	2.99×10^{-6}	4.2×10^{-11}	2.99×10^{-6}
6	1 car	Yard Personnel	No crew	Outside of yard radius	2.26×10^{-5}	6.90×10^{-9}	2.26×10^{-5}
7-20	#miles in segment	None	Train crew, 2 directions	Within radius of incident, less R.O.W area	$\sum = 1.18 \times 10^{-5}$	1.60×10^{-9}	1.18×10^{-5}

TABLE 4.5 (cont)

Segment	Shipment Units	Exposure			$\Sigma L(i)sL(j/i)L(k/j)C(jk)s$	Emergency Personnel $(\Sigma L(i)SL(j/i))\cdot .0001$	Total Risk
		Terminal	Mode	Public			
21	1 car	Yard personnel	No crew	Outside of yard radius	2.26×10^{-5}	6.9×10^{-9}	2.26×10^{-5}
22	5 miles	None	Train crew 2 directions	Within radius of incident, less r.o.w. area	3.90×10^{-7}	1.3×10^{-10}	3.90×10^{-7}
23	1 car	Marine terminal area personnel + personnel in harbor	Train crew 1 direction	Outside of marine terminal area	5.66×10^{-7}	3.1×10^{-10}	5.66×10^{-7}
24-27	1980 boxes (Segment 24) 55 pallets (Segment 25) 1 ship (Segments 26, 27)	Marine terminal area + harbor	Crew of ship, No train crew	Outside of of marine terminal area	3.65×10^{-4}	1.8×10^{-9}	3.65×10^{-4}
28	1 ship	Personnel in harbor	Crew of ship	None	2.50×10^{-4}	1.2×10^{-9}	2.50×10^{-4}
29	1500 miles	None	Crew of Ship	None	1.63×10^{-4}	—	1.63×10^{-4}
30	1 Ship	Personnel in harbor	Crew of ship	None	2.50×10^{-4}	1.2×10^{-9}	2.50×10^{-4}
31-34	1 ship (Segments 31, 32); 55 pallets & (Segment 33); 1980 boxes (Segment 34)	Marine terminal area + harbor	Crew of ship	Outside of terminal	3.66×10^{-4}	1.8×10^{-9}	3.66×10^{-4}

TABLE 4.5 (cont)

Segment	Shipment Units	Exposure Terminal	Exposure Mode	Exposure Public	$\Sigma L(i)sL(j/i)L(k/j)C(jk)s$	Emergency Personnel $(\Sigma L(i)SL(j/i))\cdot.0001$	Total Risk
35	1980 boxes	Magazine personnel	No crew	None	8.47×10^{-6}	2.8×10^{-10}	8.47×10^{-6}
					AGGREGATED FATALITY RISK		1.49×10^{-3}

TABLE 4.6

FATALITY RISK CALCULATION FOR CAE, BESSEMER TO PANAMA (AIR)

Segment	Shipment Units	Exposure: Terminal	Exposure: Mode	Exposure: Public	$\Sigma L(\cdot)sL(j/i)L(k/j)C(jk)s$	Emergency Personnel $\Sigma L(i)sL(j/i)$ .0001	Total
1	1980 boxes	Loading dock personnel	Truck drivers	None	7.42×10^{-6}	1.1×10^{-9}	7.42×10^{-6}
2-6	# miles in segment, 3 trucks	None	Truck drivers	Within radius of incident, less right of way area	$\Sigma = 6.12 \times 10^{-5}$	1.8×10^{-9}	6.12×10^{-5}
7,8	1980 boxes (Segment 7) 55 pallets (Segment 8)	cargo-only area personnel	Plane crew, truck drivers	None	4.49×10^{-5}	5.0×10^{-7}	4.49×10^{-5}
9	1 departure	cargo-only area personnel	Plane crew	None	7.55×10^{-7}	8.5×10^{-11}	7.55×10^{-7}
10,11	1 departure	Runway area personnel	Plane crew	None	7.35×10^{-7}	8.5×10^{-11}	7.35×10^{-7}
12-29	1900 miles	None	Plane crew (except for "impact" accident type; none)	None (except for "impact" accident type: public within radius of incident)	$\Sigma = 8.19 \times 10^{-6}$	1.4×10^{-9}	8.19×10^{-6}
30,31	1 departure	Runway area personnel	Plane crew	None	1.60×10^{-5}	9.9×10^{-10}	1.6×10^{-5}
32	1 departure	Cargo-only area personnel	Plane crew	None	7.55×10^{-7}	8.5×10^{-11}	7.55×10^{-7}

TABLE 4.6 (cont)

Segment	Shipment Units	Exposure: Terminal	Exposure: Mode	Exposure: Public	$\Sigma L(i)sL(j/i)L(k/j)C(jk)s$	Emergency Personnel $(\Sigma L(i)sL(j/i))\cdot .0001$	Total Risk
33,34	55 pallets (Segment 16) 1980 boxes (Segment 17)	Cargo-only area personnel	Plane crew, truck drivers	None	4.49×10^{-5}	5.0×10^{-8}	4.49×10^{-5}
35	34 miles, 3 trucks	None	Truck drivers	Within radius of incident, less r.o.w. area	1.41×10^{-5}	6.0×10^{-9}	1.41×10^{-5}
36	1980 boxes	Magazine personnel	Truck drivers	None	2.12×10^{-5}	2.9×10^{-9}	2.12×10^{-5}
					AGGREGATED FATALITY RISK		2.20×10^{-4}

TABLE 4.7

FATALITY RISK CALCULATION FOR FCL, ONTARIO TO McCOOK (NON-AIR)

Segment	Shipment Units	Exposure: Terminal	Exposure: Mode	Exposure: Public	$\Sigma L(i)SL(j/i)L(k/j)C(jk)S$	Emergency Personnel $(\Sigma L(i)SL(j/i)):0001$	Total Risk
1	8.8 equivalent cars	Plant personnel, plus loading personnel	None	Outside limits of plant	5.36×10^{-6}	7.0×10^{-10}	5.36×10^{-5}
2	8.8 equivalent cars	plant personnel,	Train crew in one direction	outside limits of plant	2.15×10^{-4}	3.0×10^{-9}	2.15×10^{-4}
3	191 miles, 8.8 equivalent cars	None	Train crew both directions	Within radius of incident, less r.o.w. area	1.71×10^{-4}	5.0×10^{-7}	1.71×10^{-4}
4	8.8 equivalent cars	Yard personnel	None	Outside limits of yard	6.29×10^{-4}	8.0×10^{-8}	6.29×10^{-4}
5-59	# of miles in segment, 8.8 equivalent cars	None	Train crew, both directions	Within radius of incident, less r.o.w. area	L.Den - 6.68×10^{-4} M.Den - 1.97×10^{-4} H.Den - 3.48×10^{-3}	3.2×10^{-6} 2.8×10^{-7} 4.1×10^{-7}	6.71×10^{-4} 1.97×10^{-4} 3.48×10^{-3}
60	8.8 equivalent cars	Yard personnel	None	Outside limits of yard	2.34×10^{-3}	8.0×10^{-8}	2.34×10^{-3}
61	6 miles, 8.8 equivalent cars	None	Train crew both directions	Within radius of incident, less r.o.w. area	2.74×10^{-4}	1.5×10^{-8}	6.74×10^{-4}
62	8.8 equivalent cars	Storage facility personnel	Train crew in one direction	Outside limits of facility	9.33×10^{-3}	1.5×10^{-9}	9.33×10^{-3}

TABLE 4.7 (cont)

Segment	Shipment Units	Exposure			$\Sigma L(i)SL(j/i)L(k/j)C(jk)S$	Emergency Personnel $(\Sigma L(i)SL(j/i)):.0001$	Total Risk
		Terminal	Mode	Public			
63	8.8 equivalent car unloading	Storage facility personnel	None	Outside limits of facility	5.36×10^{-6}	7.2×10^{-10}	5.36×10^{-6}
					AGGREGATED FATALITY RISK		1.70×10^{-2}

TABLE 4.8

FATALITY RISK CALCULATION FOR FCL, ONTARIO TO McCOOK (AIR)

Segment	Shipment Units	Exposure Terminal	Exposure Mode	Exposure Public	$\Sigma L(i)sL(j/i)L(k/j)C(jk)s$	Emergency Personnel $(\Sigma L(i)sL(j/i))\cdot .0001$	Total Risk
1	20.7 eq. truck loadings	Plant personnel plus loading personnel	Truck drivers	Outside of plant limits	1.36×10^{-4}	3.1×10^{-8}	1.36×10^{-4}
2,3	# of miles in segment, 20.7 eq. trucks	None	Truck drivers	Within radius of incident, less r.o.w. area	4.98×10^{-4} 9.68×10^{-4}	4.1×10^{-9} 4.1×10^{-9}	4.98×10^{-4} 9.68×10^{-4}
4	20.7 eq. aircraft loading	Cargo-only personnel	Truck drivers, plane crew	None	2.26×10^{-4}	2.1×10^{-8}	2.26×10^{-4}
5	6.9 eq. departures	Cargo-only personnel	Plane crew	None	1.65×10^{-6}	1.6×10^{-11}	1.65×10^{-6}
6,7	6.9 eq. departures	Runway area personnel	Plane crew	None	8.83×10^{-6} 1.46×10^{-4}	1.9×10^{-11} 3.1×10^{-10}	8.83×10^{-6} 1.46×10^{-4}
8-52	# of miles in segment, 6.9 eq. aircrafts	None	Plane crew (except "impact" accident tye: none)	None (except "impact" accident type: public within radius)	L.Den. - 3.42×10^{-5} M.Den. - 4.06×10^{-6} I.Den. - 3.31×10^{-5}	1.4×10^{-7} 8.2×10^{-9} 1.9×10^{-8}	3.44×10^{-5} 4.06×10^{-6} 3.31×10^{-5}
53,54	6.9 eq departures	Runway area personnel	Plant crew	None	3.14×10^{-4} 8.83×10^{-6}	6.6×10^{-10} 1.9×10^{-10}	3.14×10^{-4} 8.33×10^{-4}
55	6.9 eq. departures	Cargo-only personnel	Plane crew	None	1.65×10^{-6}	1.5×10^{-11}	1.65×10^{-6}

TABLE 4.8 (cont)

Segment	Shipment Units	Exposure Terminal	Exposure Mode	Exposure Public	$\Sigma L(i)sL(j/i)L(k/j)C(jk)s$	Emergency Personnel $(\Sigma L(i)sL(j/i))\cdot .0001$	Total Risk
56	20.7 eq. aircraft unloadings	Cargo only personnel	Truck drivers, plane crew	None	2.26×10^{-4}	2.1×10^{-8}	2.26×10^{-4}
57,64	# of miles in segment, 20.7 eq. trucks	None	Truck drivers	Within radius of incident, less r.o.w. area	1.89×10^{-2}	1.8×10^{-8}	1.89×10^{-2}
65	20.7 eq. truck unloadings	Storage facility personnel	Truck drivers	Outside limits of facility	2.73×10^{-3}	3.1×10^{-9}	2.73×10^{-3}
					AGGREGATED FATALITY RISK		2.00×10^{-2}

(i.e., crew) will always be involved, except at a rail yard or during loading or unloading at a siding. Therefore, the "exposure" column in Tables 4.5 through 4.8 is included in order to describe the "parties at risk" connected with each segment. Once this aspect is understood, the steps outlined in Section III (Figure 3.7) can be applied to calculate C(jk)s.

Note that for the in-transit segments in all four routes, specific risk values for each segment are not given; rather, the values shown indicate the range of segment risks over that portion of the route which is designated as "in-transit", "in-flight" or "line-haul." These are shown for low density, medium density, and high density segments.

Terminal and mode personnel exposure values are given in Section III (Tables 3.15 through 3.18); public exposure depends on average personnel density in the county in question, given in Section III (Table 3.19) for the CAE non-air sample route only.

The "emergency personnel" column uses the fatalities-per-incident rate of .0001. Risk to terminal, crew, and public personnel is added to risk to emergency personnel to produce "total risk" for the segment. It should be noted that, while the fatality risks to emergency personnel are in most cases very small compared to the fatality risks to terminal, crew, and public personnel, the injury risks to emergency personnel are in many cases not as negligible. Fatality risks to emergency personnel have been shown in Tables 4.5-4.8, however, to show the complete exercising of the model. In a few segments the emergency personnel risk is listed as N/A, due to the location of the segment (on open seas, for example).

Total fatality risk for each of the FCL routes is found by simply adding the segment fatality risks along the route. Total fatality risk for each of the CAE routes is found by aggregating the segment fatality risks along the route as described in Section III of this report.

EXPOSURE CONFIGURATIONS

The following assumptions are made in regard to the presence and configuration of parties at risk shown in the "exposure" column of Tables 4.5 through 4.8.

CAE, Bessemer to Panama (non-air), Tables 4.1 and 4.5

An incident during a rail loading operation at a plant loading dock will involve only the loading dock personnel, since the train (with its crew) has not yet arrived to pick up the car, the plant personnel are at a safe-separation distance from the loading dock, and the public is at a safe-separation distance from the plant.

An origin terminal operations incident will involve the loading dock personnel plus the crew of the half of the train which comes onto the siding to pick up the loaded car.

A line haul incident will involve the crew of the intact train, only that portion of the public not in the rail right of way, and no terminal personnel. An accident would not necessarily have killed train crew members; they are therefore counted as exposed to incident effect.

A yard operations incident will involve yard personnel in all directions from the incident, no crew (they have been dispersed throughout the yard during this phase), and only that portion of the public outside of but adjacent to the yard limits.

An incident during destination terminal operations at a marine terminal will involve the crew of the half of the train which comes onto the siding to deliver the car, plus the marine terminal area and harbor area personnel, plus members of the public outside of the marine terminal area. No CAE ship crew members are as yet present.

A transfer (rail to marine) operation incident or a marine moored or undocking incident will involve the personnel at the marine terminal area and the personnel in the harbor area (each area is a semicircle having the radius of the severity level in question), plus the crew of the ship being loaded, plus members of the public within the land-side semicircle of effect (less the terminal area semicircle). Rail crew members are not present, as the train has departed as soon as the CAE car was uncoupled, before the ship arrived at the dock.

An incident during marine harbor transit will involve ship crew and harbor personnel only, as the radius of the harbor is larger than the largest severity level radius.

An ocean transit incident will involve ship crew only, as the chance of meeting another vessel at the time of the incident on open waters is quite small. Ship crew members are counted as exposed because an accident would not necessarily have resulted in their deaths.

An incident during marine docking, moored, and unloading operations would involve the ship crew, the terminal (land-side and harbor) personnel, and the public outside of the terminal. In the case where the cargo is to be transferred to trucks, highway crew (i.e., drivers) would also be present waiting for the ship to dock. In this case, however, the cargo is not being transferred to another mode, so no other mode crew is present.

An incident during handling and unloading of rail cars at the magazine would involve only the magazine personnel; the public is at a safe-separation distance from the magazine. In the case where the cargo is brought to the magazine by truck or rail, unloading would involve the highway crew and destination terminal operations would involve the rail crew.

CAE, Bessemer to Panama (air), Tables 4.2 and 4.6

An incident during a highway loading operation involves loading dock personnel, drivers of all 3 trucks (they are assumed to be loaded at the same time), and no public.

An incident during highway transit involves the driver of only one truck (the others are far enough ahead or behind that they are not affected) plus members of the public within the incident radius but outside of the right of way of an interstate highway. An accident would not necessarily have killed the drivers and they are, therefore, counted as exposed to incident effect.

An incident during highway-to-air or air-to-highway transfer involves the personnel in the cargo-only area of the terminal but not those in the rest of the airport, since the specialized cargo-only area is separated and barricaded from the passenger operations. Plane crew and truck drivers for all 3 trucks are exposed, since the cargo is shifted onto the aircraft directly from the trucks. No public is exposed, as the airport is located at a safe-separation distance from the public.

An incident during the air static operations phase involves only the cargo-only area personnel and the plane crew; the trucks have driven away or have not yet arrived.

An incident during taxi, take-off or landing operations involves the general airport personnel and the plane crew (they are not necessarily killed by an accident).

An incident during air in-flight operations involves the plane crew, but no public on the ground, if the incident has been precipitated by a non-impact accident (accidents which do not involve impact may allow for crew survival; the incident occurs in the air where no members of the public are exposed). An incident precipitated by an impact accident (i.e., crash) involves no crew members (they have been killed by the crash), but involves members of the public during over-land segments, since the incident occurs on the ground.

An incident during highway unloading operations at a magazine involves the truck drivers (all 3 trucks are assumed to be at the magazine at once), the magazine personnel, and no public (due to safe separation distance of magazine).

FCL, Ontario to McCook (non-air), Tables 4.3 and 4.7

An incident during a rail loading operation involves plant personnel (plant is adjacent to rail loading site) plus personnel overseeing loading operation, no rail crew (train has not yet come to pick up car), and members of the public outside of the plant limits (where incident radius reaches sufficient distance). No safe separation requirements similar to those of CAE manufacture are assumed.

An incident during rail origin terminal operations involves plant and loading personnel, train (switching) crew and the public.

An incident during rail line haul operations involves entire train crew and that portion of the public which is outside of but adjacent to the rail right of way area.

An incident during rail yard operations involves yard personnel and public outside of the yard.

An incident during rail destination terminal operations involves the storage/distribution facility personnel, train (switching) crew and the public outside the limits of the facility. No safe separation requirements are assumed.

An incident during rail unloading operations involves the storage/distribution facility personnel, the public, and no train crew (the train has already departed). No distribution truck drivers are on the scene.

FCL, Ontario to McCook (air), Tables 4.4 and 4.8

An incident during a highway loading operation involves plant personnel, personnel overseeing the loading operation, drivers for one truck (trucks are loaded as separate shipments) and the public outside of the plant limits.

An incident during a highway in-transit segment involves truck drivers for one truck and members of the public outside the right of way of an interstate highway.

An incident during an aircraft loading or unloading operation (i.e., highway-to-air or air-to-highway transfer) involves cargo-only area personnel, truck drivers for 3 trucks, and the plane crew.

An incident during air in-flight operations involves the plane crew and no members of the public if the incident is precipitated by a non- impact accident. If the incident follows an impact accident, no crew members are involved; members of the public are involved (within the incident radius) for segments over land.

A highway unloading incident involves the storage/distribution facility personnel, the drivers of one truck, and that portion of the public which is outside but adjacent to the limits of the facility. No other trucks are exposed at the time of the unloading operation.

FACTORS AFFECTING TOTAL RISK

Several segments have been chosen from the four route alternatives described above in order to give some examples of the usefulness of the model in accounting for and in highlighting the factors influencing overall risk.

CAE, Bessemer Alabama, to Mindy Docks, Canal Zone, Air Route vs. Non-Air Route

The expected number of fatalities resulting from the shipment of 49.5 tons of dynamite by the air route is 2.2×10^{-4} (Table 4.6) compared with 1.49×10^{-3} for the rail-marine route (Table 4.5). The principal contributing factors to the non-air route risks are shown in Table 4.5 and discussed below.

Marine Terminal Operations. The total expected fatalities from marine terminal operations is 5×10^{-4}. This value is heavily influenced by the large number of crew members who would be in the immediate vicinity of

fires, fireballs, and explosions. The expected fatalities are influenced to a lesser degree by the population in the dock area; however in general, these are expected to contribute more heavily to injuries than fatalities.

Handling of Packages. The handling of packages at Bessemer (Segment 1) involves only workers at the loading dock and expected fatalities are 2.47 x 10^{-6}. The rail-marine loading at Gulfport, Miss. (Segments 24-27), however, involves both the handling of 1980 boxes and the crane handling of 55 pallets in a heavily populated area. Crew members, terminal area workers, and the public in the vicinity would be exposed, and expected fatalities of 3.65 x 10^{-4} result. The handling at Mindy Docks involves pallet handling and box handling at the Dock Area (Segments 31-34) and handling of boxes at the magazine (Segment 35). Total fatalities for the operation are expected to total 3.74 x 10^{-4}.

Ship Transit. Expected fatalities of 1.63 x 10^{-4} are, of course, due entirely to exposure of the ship's crew.

Rail Yards and Terminals contribute an expected total of 6.97 x 10^{-5} fatalities, including train crewmen, yard personnel and the public adjacent to the rail right of way.

In the air route, the handling of packages and the highway tranport segments present the most risks; however, the airport operations also are of significance.

Handling of packages for the air mode consists of hand carrying 1980 boxes and handling 55 pallets in a manner similar to those used in the non-air modes. However, because of the large land areas occupied by airports, only flight crews and cargo personnel are exposed and total expected fatalities from all handling operations are 1.18 x 10^{-4}.

Highway Transport Operations contribute an estimated 6.12 x 10^{-5} fatalities, with truck drivers and the public immediately adjacent to highways being exposed.

Airport Operations contribute an estimated 7.94 x 10^{-5} fatalities with only the plane crew and airport cargo handlers being exposed.

FCL, Ontario to McCook, Air Route vs. Non-Air Route

For the same amount of material the expected number of fatalities is slightly higher for the air route than for the non-air route, although the two values are quite close. Segments most significantly affecting the .0171 value for the non-air route are the rail yarding segments (#4 and #60) and those rail line haul and terminal operations segments which are located in Cook County, Illinois (#s 59, 61, and 62). The segments most significantly affecting the .0200 value for the air route are the truck shipment and unloading operations in Cook County, Ill. (#57-64, 65). The following analysis shows why these segments are associated with the higher values for fatality risk. Table 4.9 has been included at this point to show the derivation of specific risk values for these two routes. Expressions in this table have been found using the expected value model for FCLs described in Section III (Volume I).

Yarding: San Bernardino County and Cook County. The base value used for a yarding segment (from Table 4.9) was 6.18 x 10^{-4}. This value is based on exposure of yard personnel and on the incident rates associated with yarding scenarios; it is higher than the fatality base values (i.e., values independent of demographic characteristics of the particular segment) for any of the other rail segment types. Note that in segment #4, San Bernardino County, this base value is affected very little by the addition of the density related term (2.9 x 10^{-7} times population density); however, in Cook County, segment #60, where the population density is almost 200 times that of San Bernardino, the base value is affected considerably by the addition of this term. Thus, both yarding segments show high values for fatality risk due to relatively high terminal personnel exposure and incident rates, but the Cook County segment shows even further risk due to its higher population density outside the yard area.

Line Haul: Cook County. Line haul segments on this route were found to show fatality risk values of 10^{-5} or 10^{-6}, in general. The two line

TABLE 4.9

EXPRESSIONS FOR INJURY, FATALITY, AND PROPERTY DAMAGE
RISK VALUES BY FCL PHASE OF OPERATION

Phase		Injury	Fatality	Property Damage
Highway,	Loading	$1.59 \times 10^{-4} + 4.30 \times 10^{-7}D$	$1.34 \times 10^{-4} + 7.3 \times 10^{-8}D$	$102.8 + 4.38 \times 10^{-8}D$
	Unloading	$1.04 \times 10^{-4} + 5.73 \times 10^{-7}D$	$4.62 \times 10^{-5} + 4.52 \times 10^{-7}D$	$11.1 + 2.11 \times 10^{-7}D$
	In-transit	$(4.71 \times 10^{-7} + 9.90 \times 10^{-8}D)M$	$(1.80 \times 10^{-6} + 3.43 \times 10^{-7}D)M$	$(.28 + 8.55 \times 10^{-8}D)M$
Rail,	Loading	3.83×10^{-5}	5.36×10^{-6}	2.74
	Unloading	3.83×10^{-5}	5.36×10^{-6}	$.4 + 2.96 \times 10^{-9}D$
	Origin Term.	$7.01 \times 10^{-5} + 3.95 \times 10^{-6}D$	$2.15 \times 10^{-4} + 2.64 \times 10^{-6}D$	$18.0 + 1.74 \times 10^{-6}D$
	Dest. Term.	$7.90 \times 10^{-6} + 2.11 \times 10^{-6}D$	$2.01 \times 10^{-5} + 1.57 \times 10^{-6}D$	$20.1 + 9.43 \times 10^{-7}D$
Rail,	Yarding	$7.15 \times 10^{-4} + 1.74 \times 10^{-6}D$	$6.18 \times 10^{-4} + 2.90 \times 10^{-7}D$	580.3
	Line Haul	$(1.59 \times 10^{-7} + 2.63 \times 10^{-8}D)M$	$(2.53 \times 10^{-7} + 1.89 \times 10^{-8}D)M$	$(.39 + 1.19 \times 10^{-8}D)M$
Air,	Loading/ Unloading	1.74×10^{-4}	2.26×10^{-4}	64.6
	Static	4.16×10^{-7}	1.65×10^{-6}	.90
	Taxi	1.01×10^{-5}	8.83×10^{-6}	4.63
	Take-Off	1.66×10^{-4}	1.46×10^{-4}	76.5
	Landing	3.57×10^{-4}	3.14×10^{-4}	164.9

Note: These produce expected values based on shipment of 250,000 gallons of LH_2 (20.7 truckloads, 8.3 railcar loads).

D = Personnel or property density

M = Mileage in segment

TABLE 4.9 (cont)

Phase		Injury	Fatality	Property Damage
Air,	In-Flight	$(7.93 \times 10^{-9} + 4.12 \times 10^{-10} D)M$	$(3.14 \times 10^{-8} + 3.45 \times 10^{-10} D)M$	$(.07 + 2.89 \times 10^{-10} D)M$
Marine,	Roro, Ldg./ Unloading	4.17×10^{-5}	8.73×10^{-5}	93.5
	Moored	2.51×10^{-4}	4.93×10^{-4}	419.3
	Dock/ Undock	1.43×10^{-4}	2.81×10^{-4}	808.1
	Harbor Transit	1.86×10^{-4}	5.23×10^{-4}	62.3
	Ocean Transit	$(5.66 \times 10^{-8})M$	$(8.10 \times 10^{-8})M$	(.0450)M
	Barge Loading	$1.55 \times 10^{-6} + 5.47 \times 10^{-7} D$	$1.96 \times 10^{-6} + 1.31 \times 10^{-7} D$	$14.1 + 1.54 \times 10^{-6} D$
	Moored	$1.16 \times 10^{-4} + 8.34 \times 10^{-6} D$	$2.07 \times 10^{-4} + 6.58 \times 10^{-6} D$	$78.9 + 6.17 \times 10^{-6} D$
	Docking	$8.0 \times 10^{-6} + 9.65 \times 10^{-7} D$	$3.12 \times 10^{-5} + 8.24 \times 10^{-7} D$	$42.9 + 7.59 \times 10^{-7} D$
	Undocking	$1.54 \times 10^{-5} + 1.50 \times 10^{-6} D$	$5.46 \times 10^{-5} + 7.52 \times 10^{-7} D$	$103.9 + 7.06 \times 10^{-7} D$
	In Transit GIWW	3.0×10^{-5}	1.24×10^{-5}	28.2
	Harbor Transit	3.52×10^{-5}	9.94×10^{-5}	117.2

D = Personnel or property density

M - Mileage in segment

haul segments in Cook County, however, showed fatality risks of 1.91×10^{-3} and 6.8×10^{-4}, respectively, for the segment immediately before and the segment immediately after the yarding segment. Mileage in each of these segments was no higher than that in any of the other line haul segments along the route; therefore, the difference was due to the substantially higher population density of that county.

<u>Destination Terminal Operations: Cook County</u>. The fatality risk value of 9.33×10^{-3} for terminal operations at the destination (storage facility) is almost completely determined by the county density. The fatality risk associated with the public outside of the storage facility area overshadows that risk associated with facility personnel and train crew, due to the high population density of the county. The expression, $(2.01 \times 10^{-5} + (1.57 \times 10^{-6} \times \text{population density})$, from Table 4.9, used for destination terminal segments, would have given a value for risk which would be one or two orders of magnitude lower if the county population density were low enough that the first term in this expression (representing crew and terminal personnel) were the more significant term.

Expected fatalities on the air route are influenced mainly by the highway loading and unloading segments, the highway in-transit segments through densely populated areas and the air landing, take-off, loading, and unloading segments. Note that the total of the fatality risks for <u>all</u> in-flight segments is less than the risk for just one of these other segments. The following analysis, relying again on reference to Table 4.9, is given in order to show why these relationships occur.

<u>Highway, In-transit</u>. These values are affected substantially by mileage and by area density and are generally on the order of 10^{-3} or 10^{-4}, most segments having less than a 50-mile transit through a county. The short (9-mile) transit through Cook County in Segment 64, however, shows a higher risk value (5.28×10^{-3}), which is due to the higher population density of this county. Note that in general, highway in-transit segments show greater fatality risk than do rail in-transit segments. This is due to 1) a difference in incident likelihood, and 2) the greater proximity of the highway crew (drivers) to the inner severity radius where fatalities are very likely.

Highway Loading and Unloading. The risk associated with the highway unloading segment is an order of magnitude greater than that associated with the loading segment, due to the smaller non-public terminal area associated with the former. With the aid of Table 4.9, it can also be noted that unloading in Cook County involves risk to members of the public in more areas outside of the area than does loading in San Bernardino County. Of course, there is more risk to terminal personnel during loading because of the greater number of personnel in the vicinity of the plant than at the storage facility, but this risk is overshadowed by the effect of population density. Both of these segments show relatively high values for fatality risk, as compared with other modes.

Air loading, Unloading, Take-off, Landing. These segments show fatality risk values on the order of 10^{-4}, due to the incident likelihood associated with certain scenarios and the number of personnel in the vicinity of the cargo-only area and in the entire airport. Note from Table 4.9 that these values are not dependent on population density outside of the airport, since these terminals are assumed to be far enough removed from the public that these personnel will not be affected.

Air, In-flight. The expression from Table 4.9 used to calculate fatality risk for these segments shows that risk is lower than for highway in-transit or rail line haul segments of similar mileage, unless the air segment density is so large that the small value for risk to crew becomes insignificant. In general in-flight segments show fatality risks on the order of 10^{-6} and 10^{-7}; this is due to: 1) the low incident rate during this phase; 2) the reduced public exposure implied by the fact that some of the scenarios connected with this phase result in incidents in mid-air, with no risk to the public on the ground; and 3) the reduced crew personnel exposure for scenarios resulting in crash-precipitated incidents with no risk to the crew (who are already affected by the accident).

V. RISK ASSESSMENT RESULTS

This section contains the results of the risk assessment calculations. It discusses estimates and observations specific to each of the material types (CAE and FCL) as well as results common to both hazardous material types. In addition, applications of these results to Materials Transportation Bureau regulations and program efforts are addressed.

CLASS A EXPLOSIVES

Table 5.1 shows the risks, in terms of expected number of injuries, fatalities, and dollars of property damage, associated with the air and non-air route alternatives for each of the six CAE origin-destination pairs. Risks are for shipment of 49.5 tons of explosives, and have been found through computerized application of the expected value model.

As shown in Table 5.1, the relative risks of the air alternatives are generally lower than their respective non-air alternative routes. For these shipments of Class A explosives, only 2 of the 18 risk measures for air route alternatives (i.e., highway-air-highway) are higher than their non-air route counterparts. These two exceptions involve property damage ($153) for the Bessemer to Frackville route and fatalities (2.20×10^{-4}) for the Bessemer to Mindy Docks shipment. For the shipments originating in Port Ewen, N.Y., the air risks for injuries and fatalities are lower than the non-air alternatives by more than an order of magnitude.

TABLE 5.1

RISKS ASSOCIATED WITH CAE ROUTES

Origin-Destination	Route Alternative	Risk (per shipment of 49.5 tons of dynamite)		
		Injuries	Fatalities	Property Damage ($)
Bessemer, ALA to Frackville, PA	Non-air (highway)	5.49×10^{-4}	4.95×10^{-4}	50
	Air alternative	1.69×10^{-4}	1.44×10^{-4}	153
Radford, VA to Yorktown, VA	Non-air (rail)	1.45×10^{-4}	1.21×10^{-4}	399
	Air alternative	2.04×10^{-4}	2.28×10^{-4}	192
Carthage, MO to Frackville, PA	Non-air (rail-hwy.)	3.94×10^{-4}	2.94×10^{-4}	893
	Air alternative	1.14×10^{-4}	1.67×10^{-4}	172
Bessemer, ALA to Mindy Docks, Panama	Non-air (rail-ship)	7.04×10^{-4}	1.49×10^{-3}	5,937
	Air alternative	1.73×10^{-4}	2.20×10^{-4}	176
Port Ewen, NY to St. Thomas, VI	Non-air (rail-ship)	1.58×10^{-3}	2.22×10^{-3}	8,872
	Air alternative	8.56×10^{-5}	9.75×10^{-5}	172
Port Ewen, NY to Saudi Arabia	Non-air (hwy-ship)	2.02×10^{-3}	2.78×10^{-3}	7,699
	Air alternative	8.65×10^{-5}	9.80×10^{-5}	172

FLAMMABLE CRYOGENIC LIQUIDS

Table 5.2 shows the risks associated with the air and non-air route alternatives for each of the six FCL origin-destination pairs. Risks are for shipment of a total of 250,000 gallons of material (in separate shipment units depending on the mode), and have been found through manual application of the expected value model.

These LH_2 shipment results shown in Table 5.2 indicate a similar risk relationship between air and non-air route alternatives. For LH_2 only 4 of the 18 risk measures indicate that air risks are higher than their non-air counterparts; and, in each of these four instances, the differences are extremely small. Moreover, in several of the comparisons where air risks are lower, the difference is more than an order of magnitude.

GENERAL OBSERVATIONS

The following observations have been developed from a segment-by-segment analysis for each of the twelve origin-destination pairs. They are based both on the calculations presented in Tables 5.1 and 5.2 and on the segment risk distribution information presented in Attachment A of this section.

Route Dependency

The comparative risk assessment model ultimately compares entire alternative routes for a given origin-destination pair. Route comparison requires assessment of modal combinations such as truck-air-truck or rail-barge-rail, not exclusive modes. In turn, such comparisons incorporate different cargo capacities and crew sizes, and travel different rights-of-way through different population centers. The comparative risk assessment, therefore, is highly route dependent.

Because of the route-dependent nature of the risk measurements, it was found that rerouting of a shipment to avoid high population density segments can reduce risk for each of the modes. For example, rerouting of an LH_2 shipment to avoid Cook County, Illinois, significantly reduced both air

TABLE 5.2

RISKS ASSOCIATED WITH LH_2 ROUTES

Origin-Destination	Route Alternative	Risk (per shipment of 250,000 gallons)		
		Injuries	Fatalities	Property Damage ($)
Ashtabula, OH to Suffield, CONN	Non-air (highway)	2.1×10^{-2}	7.0×10^{-2}	431
	Air alternative	3.0×10^{-3}	4.0×10^{-3}	538
Long Beach, CA to Flagstaff, AZ	Non-air (rail)	1.0×10^{-2}	7.0×10^{-3}	805
	Air alternative	9.0×10^{-3}	5.8×10^{-3}	604
New Orleans, LA to Bay St. Louis, MISS	Non-air (marine)	3.2×10^{-2}	2.3×10^{-2}	2,208
	Air alternative	0.7×10^{-2}	1.5×10^{-2}	532
New Orleans, LA to Brest, France	Non-air (marine)	8.0×10^{-3}	1.4×10^{-2}	5,184
	Air alternative	9.0×10^{-3}	1.5×10^{-2}	931
Ontario, CA to McCook, ILL	Non-air (rail)	3.3×10^{-2}	1.7×10^{-2}	1,871
	Air alternative	1.3×10^{-2}	2.0×10^{-2}	738
Ashtabula, OH to St. Thomas, VI	Non-air (highway)	2.6×10^{-2}	9.2×10^{-2}	5,360
	Air alternative	2.0×10^{-3}	2.0×10^{-3}	641

and rail risk measures. (This point is made dramatically clear in the Risk Profile discussion later in this section.)

The influence that particular routes exert on risk measures is further evidenced by the fact that risk measures -- injury, fatality, property damage -- may also vary within the same mode. For instance, marine fatality risk might be higher than injury risk along one route and lower than injury risk on another. This relationship among risk measures is due to the severity level vs. the population density associated with the three (modularized) severity radii.

Air Risks

With proper attention to airport selection, airport handling and related highway staging operations, the risk of shipping hazardous materials by air can be made significantly less than that for other modes. Despite the fact that the risk assessment model compares routes and not modes exclusively, the majority of the route alternatives involving the air mode (i.e., truck-air-truck) have resulted in the lowest risk estimates for injuries and fatalities for the types of hazardous materials studied. The air routes, however, generally have higher property damage losses due to airport terminal areas. In addition, the highway portions of the air routes contribute more to the injury and fatality levels (more than air).

The chief reason for the lower air risks is due to the low risk characteristic of the in-flight phase. A corollary of this relationship is that air is relatively safer over longer distance routes, since its risks are more nearly dependent upon departure rate and are less distance-related.

Highway Risks

The relatively high truck accident rate and the dense populations through which highways travel give the highway mode a relatively high risk, particularly with regard to injury and fatality measures. The highway portions of both the air and non-air route alternatives show the high risk contributed by the highway mode.

Rail Risks

With the rail oriented route alternatives, densely populated rail terminal areas contribute high probabilities for all three risk measures: injuries, fatalities, and property damage.

Marine Risks

For marine route alternatives, the large amounts of material carried on a single vessel (i.e., barge or ship) plus the loss potential at marine terminal facilities dominate the marine mode risks. The highway portions o marine routes also contribute significantly to the overall risks.

Absolute Risks

Throughout this study, absolute risk estimates were made deliberately conservative, rather than underestimate injury, fatality, and property damage values. On the other hand, the conservative nature of these estimates has been applied consistently to all modes and segments thereby maintaining a valid relationship among relative risks.

APPLICATION OF RISK PROFILES

Aside from the relative risk measures shown in Tables 5.1 and 5.2, Figures 5.1 and 5.2 illustrate the additional kinds of analyses that are made possible through use of the expected value model. For example, the risk profiles in Figure 5.1 show the change in injury risks which result from rerouting to avoid a high population (density) area --Cook County, Illinois (which contains the city of Chicago). Where Cook County is avoided in the shipping of LH_2, the injury risk for both the air and non-air alternatives is lowered considerably.

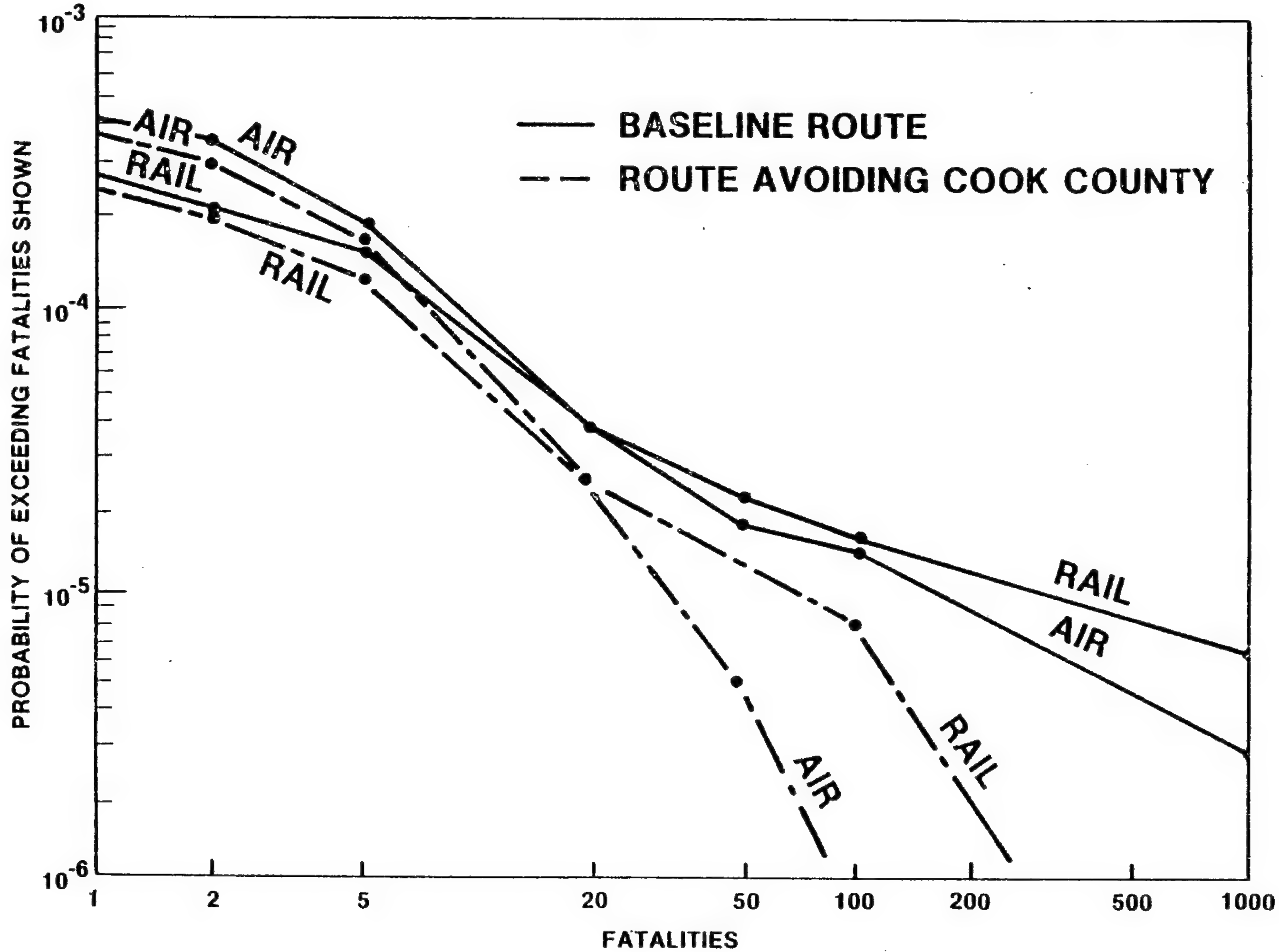


FIGURE 5.1. EFFECT OF DEMOGRAPHY ON RISKS ASSOCIATED WITH LIQUID HYDROGEN SHIPMENTS FROM ONTARIO, CA. TO McCOOK, IL. BY AIR AND RAIL ROUTES

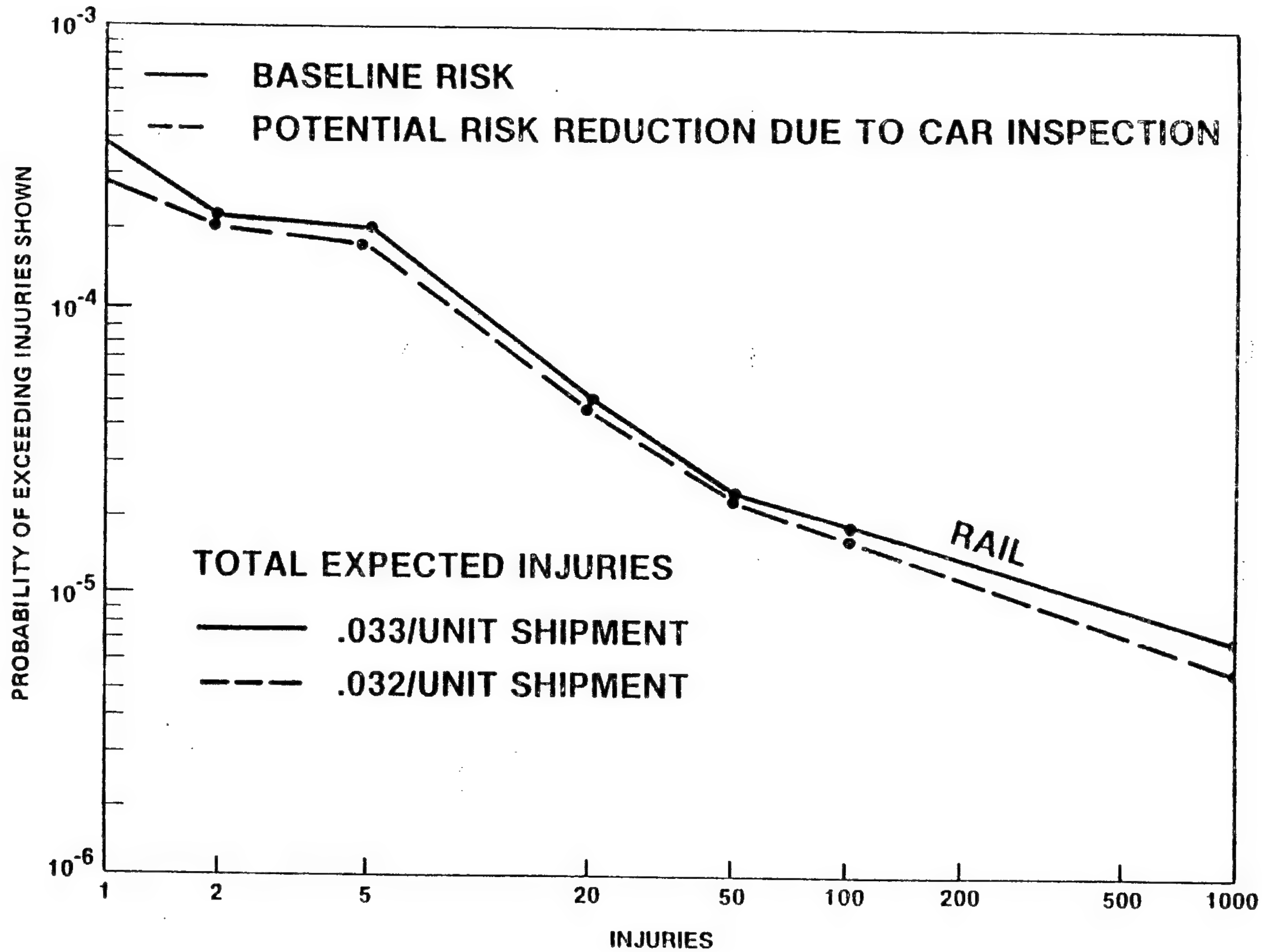


FIGURE 5.2. EFFECT OF INCREASED CAR INSPECTION ON RISKS ASSOCIATED WITH LIQUID HYDROGEN SHIPMENTS FROM ONTARIO, CA. TO McCOOK, IL. BY RAIL

The risk profile in Figure 5.2 shows the sensitivity of risk estimates to one form of safety improvement measure. In this instance, the impact of increased car inspection (both vehicle and consist-related) is shown to be very small. The capability of measuring such impacts provides an important program planning tool for hazardous materials industry regulators, in terms of both resource allocation and safety analysis work.

ATTACHMENT 5A
DISTRIBUTION OF SEGMENT RISKS

The following seven tables summarize the distribution of segment risks for the transport of LH_2 and Class A explosives. Combined with the risk measures listed in Tables 5.1 and 5.2, they provide the foundation for the observations stated in Section V.

Because the calculation of risk estimates for LH_2 shipments were not computerized, it was impractical (given time and resource constraints) to provide risk distributions for all six FCL origin-destination pairs. With CAE calculations being done by computer, the results for all six CAE origin-destination pairs (twelve routes) are presented herein.

TABLE 5A.1

DISTRIBUTION OF SEGMENT RISKS FOR SHIPMENT OF LIQUID HYDROGEN FROM ONTARIO, CA. TO McCOOK, ILL.

Transport Operations	Injuries	Fatalities	Damage
a. Rail Shipments			
• Terminal Operations at Ontario	1%	1%	--
• Yard Operations at San Bernardino	3%	4%	31%
• Line Haul Operations	19%	26%	37%
• Yard Operations at Corwith Yard, Ill.	36%	14%	31%
• Terminal Operations at McCook, Ill.	41%	55%	1%
• Total	100%	100%	100%
b. Air Shipments			
• Truck Loading at Ontario	1%	1%	14%
• Truck Transit - California	3%	7%	3%
• Airport Operations	7%	5%	52%
• Truck Transit - Illinois	62%	73%	28%
• Truck Unloading - McCook	27%	14%	3%
• Total	100%	100%	100%

TABLE 5A.2

DISTRIBUTION OF RISKS FOR SHIPMENT OF CAE
FROM CARTHAGE, MO. TO FRACKVILLE, PA.

Transport Operations	Injuries	Fatalities	Damage
a. Rail-Highway Shipments			
• Handling of Packages and Pallets	10%	22%	12%
• Rail Yard and Terminals	37%	31%	84%
• Rail Line Haul	41%	34%	4%
• Highway Transit	12%	13%	--
• Total	100%	100%	100%
b. Air Shipments			
• Handling of Packages and Pallets	39%	71%	20%
• Highway Transport	18%	11%	1%
• Airport Operations	35%	15%	79%
• Air In-flight	8%	3%	--
• Total	100%	100%	100%

TABLE 5A.3

DISTRIBUTION OF RISKS FOR SHIPMENT OF CAE
FROM BESSEMER, AL. TO FRACKVILLE, PA.

Transport Operations	Injuries	Fatalities	Damages
a. Highway Shipments			
• Handling of Packages and Pallets	2%	6%	2%
• Highway Transport	98%	94%	98%
• Total	100%	100%	100%
b. Highway Air Shipments			
• Highway Handling Package and Pallets	6%	20%	1%
• Highway Transport	62%	57%	5%
• Air Operations	28%	20%	94%
• Total	100%	100%	100%

TABLE 5A.4

DISTRIBUTION OF RISKS FOR SHIPMENT OF CAE
FROM PORT EWEN, N.Y. TO DHAHRAN, SAUDI ARABIA

Transport Operations	Injuries	Fatalities	Damages
a. Highway-Marine Shipments			
• Handling of Packages and Pallets	12%	16%	41%
• Highway Transport	59%	25%	1$
• Marine Terminal Operations	10%	19%	32%
• Ship Transit	19%	40%	26%
• Total	100%	100%	100%
b. Air Shipment			
• Handling	26%	58%	11%
• Highway Transport	2%	2%	--
• Airport Operations	70%	38%	88%
• Air In-flight	2%	2%	1%
• Total	100%	100%	100%

TABLE 5A.5

DISTRIBUTION OF SEGMENT RISKS FOR SHIPMENT OF CAE
FROM PORT EWEN, N.Y. TO ST. THOMAS, VIRGIN ISLANDS

Transport Operations	Injuries	Fatalities	Damages
a. Rail-Marine Shipments			
• Handling	16%	24%	40%
• Highway Transport	1%	1%	--
• Rail Yard Terminal	10%	5%	10%
• Rail Line Haul	47%	42%	7%
• Marine Terminal Ops.	23%	22%	40%
• Ship Transit	3%	6%	3%
• Total	100%	100%	100%
b. Air Shipments			
• Handling	26%	58%	11%
• Highway Transport	2%	2%	--
• Airport Operations	68%	38%	89%
• Air In-flight	4%	2%	--
• Total	100%	100%	100%

TABLE 5A.6

DISTRIBUTION OF SEGMENT RISKS FOR SHIPMENT OF CAE
FROM RADFORD, VA. TO YORKTOWN, PA.

Transport Operations	Injuries	Fatalities	Damages
a. Rail Shipments			
• Handling	2%	7%	--
• Rail Yard Terminal	58%	59%	97%
• Rail Line Haul	40%	34%	3%
• Total	100%	100%	100%
b. Air Shipments			
• Handling	22%	52%	18%
• Highway Transport	47%	28%	3%
• Airport Operations	28%	15%	79%
• Air In-flight	3%	5%	--
• Total	100%	100%	100%

TABLE 5A.7

DISTRIBUTION OF SEGMENT RISKS FOR SHIPMENT OF CAE
FROM BESSEMER, AL. TO MINDY DOCKS, PANAMA

Transport Operations	Injuries	Fatalities	Damage
a. Rail-Marine Shipments			
• Handling of Packages and Pallets	30%	20%	44%
• Rail Yards and Terminals	16%	10%	9%
• Rail Line Haul	4%	7%	1%
• Marine Terminal Ops.	42%	52%	41%
• Ship Transit	8%	11%	5%
• Total	100%	100%	100%
b. Air Shipments			
• Handling of Packages and Pallets	26%	54%	20%
• Highway Transport	49%	34%	4%
• Airport Operations	25%	11%	76%
• Air In-flight	--	1%	--
• Total	100%	100%	100%

OCT. 9, 1979

APPENDIX A

ANALYSIS OF EXPECTED REDUCTION IN RISK RESULTING FROM IMPROVEMENT IN LH_2 RAILCAR INSPECTION

(Performed in response to DOT comments on draft report.)

INTRODUCTION

This analysis covers the reduction in risks to be expected from an improvement in current car inspection practices for loaded LH_2 tank cars at the shippers siding and at interchange points and yards in accordance with Code of Federal Regulations Title 49.

It is assumed that improved car inspection will discover and correct all defective fittings, valves, and connectors together with loading errors (e.g., overfilling) that exist after the loading operations, as well as all car defects contributing to train accidents. Such inspections would not affect errors during loading.

Risk reduction is measured by comparing the profile of injury probabilities (probability of exceeding a particular number of injuries) based on the above assumptions versus those injury probabilities obtained from current accident/incident data.

The analysis is based on the shipment of 250,000 gal. (8.8 rail tank cars) from Ontario, California to McCook, Illinois.

Production of a Normal (Baseline) Injury Profile

A baseline injury profile for the shipment of 250,000 gal. of LH_2 from Ontario, California to McCook, Illinois is obtained through the following steps:

1. Tabulate the incident rate vs. expected number of injuries for each route segment using the incident scenarios and rates from Table 3.12

   - For example, loading at McCook involves incident types, 9, 10, 11 from Table 3.12

2. Multiply incident rates per carload by 8.8 (carloads per 250,000 gal. shipment)

3. Aggregate incident probabilities over arbitrary selected ranges of injuries (1, 2-5, 6-20, 21-50, 51-100, 100-1,000, >1,000 were used in the analysis).

   - See Table A, Column 1.

4. Starting at injuries >1,000, Plot cumulative distribution of injuries $\geq$ i.

   - See Table A.1, Column 2 and baseline curve on Figure 5.2.

Accounting for Effects of Railcar Inspection

The effects of railcar inspection are accounted for through the expected reduction in train accidents (derailment, collisions, and "other") and through the expected reduction in defects and human errors associated with fittings, valves, and connectors (FVC). Pages 8-42 through 8-47 from Volume II are included for reference.

1. From FRA accident/incident data, 1% of collisions, 3% of derailments, and 0.5% of "other" train accidents are caused by defective cars.

2. A review of HMIR data for all flammable liquids and gases indicates that about 70% of all rail incidents result from defective or misuse of fittings, valves, and connectors. These are considered under "dangerous environments" in Volume II, Table 8.8.

3. The values in Table 8.8 are revised by reducing collisions by 1%, derailments by 3%, "other" by 0.5% and "dangerous environment" accidents by 70%.

4. Disaggregation of the values in Table 8.8 by spill size results in the values in Table 8.9. The revisions of Table 8.8 from Step 3 result in the following reductions of incidents by spill size: Catastrophic 3%, serious 2%, minor 50%.

5. Association of spill size and phase of operation from Table 8.9 with the incident types in Table 8.10 and the incident scenario in Table 3.12 results in the injury reduction factors (multipliers) shown in Table A.2.

   - incident scenario 9 will result in 50% as many injuries as previously while incident scenario 10 will still have 98% as many.

6. The results in the new injury profiles shown in Table A.1, Column 3 and 4 and revised curve in Figure 5.2

Results

Although injuries due to minor spills (low loss-high probability events) would be reduced by one half, the overall risk of injury is only reduced from about .033 to .032 per 8.8 carloads because of the risk contributions due to high loss-low probability incidents.

As pointed out in the ORI report, all LH_2 risk estimates appear to be about an order of magnitude too high. A large degree of conservatism was used in estimates of (a) probability of an incident given an accident and (b) losses given an incident. This was considered advisable due to lack of sufficient LH_2 incident data (e.g., only 1 rail incident involving LH_2 in 10 years of HMIR data).

TABLE A.1

INJURY PROFILES

RAIL TRANSPORT OF LH_2; ONTARIO, CAL. TO MCCOOK, ILL.

NO. OF INJURIES	BASELINE VALVES		IMPROVED CAR INSPECTION	
	PROB.	Σ PROB.	PROB.	Σ PROB.
>1,000	8.06×10^{-6}	8.06×10^{-6}	7.85×10^{-6}	7.85×10^{-6}
100-1,000	1.63×10^{-5}	2.44×10^{-5}	1.50×10^{-5}	2.29×10^{-5}
51-100	1.18×10^{-5}	3.62×10^{-5}	1.15×10^{-5}	3.44×10^{-5}
21-50	3.31×10^{-5}	6.93×10^{-5}	3.24×10^{-5}	6.68×10^{-5}
6-20	1.54×10^{-4}	2.23×10^{-4}	1.50×10^{-4}	2.17×10^{-4}
2-5	8.91×10^{-5}	3.12×10^{-4}	7.98×10^{-5}	2.97×10^{-4}
1	1.83×10^{-4}	4.95×10^{-4}	1.48×10^{-4}	4.45×10^{-4}

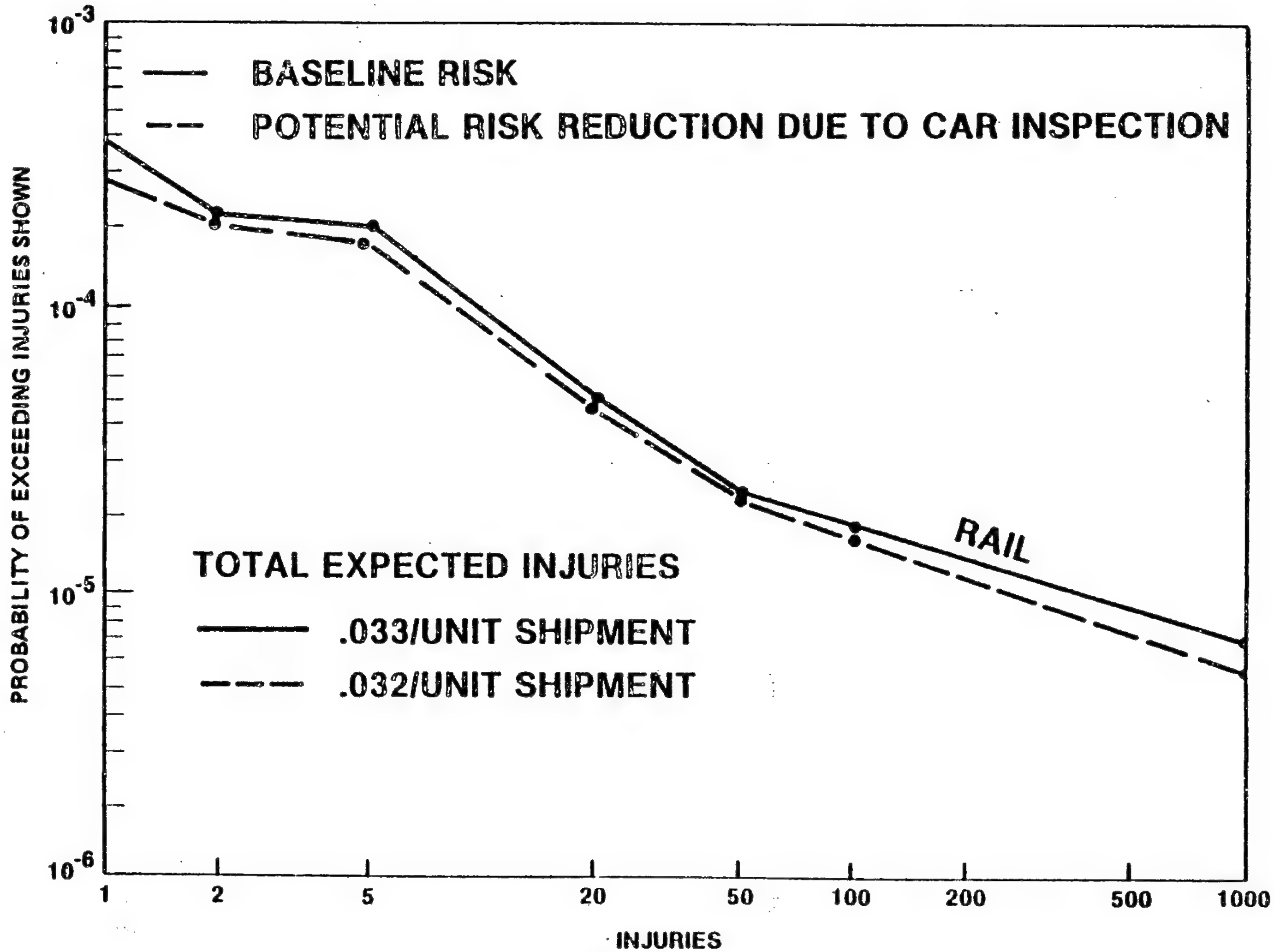


FIGURE 5.2. EFFECT OF INCREASED CAR INSPECTION ON RISKS ASSOCIATED WITH LIQUID HYDROGEN SHIPMENTS FROM ONTARIO, CA. TO McCOOK, IL. BY RAIL

TABLE A.2

INJURY REDUCTION

DUE TO IMPROVED CAR INSPECTION

SCENARIO TYPE	SPILL SIZE	REDUCTION FACTOR
9	Minor	.50
10	Severe	.98
11	Cat.	.97
12	Severe	.98
13	Severe	.98
14	Severe	.98
15	Severe	.98
16	Severe	.98
17	Cat.	.97
18	Severe	.98
19	Severe	.98
20	Cat.	.97
21	Severe	.98
22	Severe	.98
23	Cat.	.97

The following pages are pages 8-42 through 8-47 of Volume II to this report.

Loading and Unloading

1) The loading and unloading operations for rail tank cars are very similar to those used for truck trailers and the same incident likelihoods are assumed.

In-transit

1) In-transit train accidents and hazardous material cars in accidents and having incidents are listed in the FRA accident/incident bulletins. The number of hazardous material shipments can be estimated from the 1% waybill sample. Using these data results in:

(a) Annual train accidents = 9550
(b) Hazardous materials cars in accidents = 4288
(c) Fractions of shipments which are LH_2 = .0011
(d) LH_2 cars in accidents = (b) x (c) = 4.50
(e) LH_2 cars in incidents = 0.2
(f) LH_2 incidents/accidents = 0.2/4.50 = .0444

2) Incident rates by accident types from the FRA data are as shown in Table 8.7.

3) The incident/accident rates in Table 8.7 are now disaggregated by the accident rates from Risk Factors and Accident Rates: Rail (Vol. II, Sec. III). This results in the incident rates by accident types shown in Table 8.8.

TABLE 8.7

INCIDENT RATES BY ACCIDENT TYPE

Accident Type	Normalized Incident/Accident	Accidents Per 1,000	LH_2 Incident/Accident	Incident/Accident By Type
Derailment	$X_1 = 2.05X_2$	780	.0444	.0506
Collision	$X_2 = X_2$	130	.0444	.0247
Other	$X_3 = .75X_2$	90	.0444	.0185
Dangerous Environment	N/A	N/A	N/A	1.0000

Note: $2.05X_2(780) + X_2(130) + .75X_2(90) = .0444(1000)$

$X_2 = .0247,\ X_1 = 2.05X_2 = .0506$

$X_3 = .75X_2 = .0185$

TABLE 8.8

RAIL (IN - TRANSIT) INCIDENT RATES BY ACCIDENT TYPE AND PHASE OF OPERATION

Phase of Operation	Type of Accident			Dangerous Environment
	Collision	Derailment	Other	
Origin Terminal	1.07×10^{-6}	8.20×10^{-7}	1.18×10^{-8}	1.61×10^{-4}
Destination Terminal	0.62×10^{-6}	5.50×10^{-7}	2.42×10^{-9}	8.02×10^{-5}
Yard OPS	1.52×10^{-5}	2.90×10^{-5}	1.16×10^{-7}	1.61×10^{-4}
Line haul	0.49×10^{-8}	6.40×10^{-8}	1.98×10^{-9}	5.62×10^{-7}

Units: Terminal OPS = Incidents/Shipment, Yard OPS = Incidents Per. OP., Line haul = Incidents Per Car-Mile.

TABLE 8.9

RATES OF RAIL (IN-TRANSIT) INCIDENTS BY SPILL CATEGORY AND PHASE OF OPERATION

Phase of Operation	Spill Category			
	Minor		Severe (Ignite)	CAT (Ignite)
	Spill	Ignite		
Origin Terminal	1.39×10^{-4}	1.54×10^{-5}	8.43×10^{-6}	5.50×10^{-8}
Destination Terminal	6.94×10^{-5}	7.71×10^{-6}	4.24×10^{-6}	3.50×10^{-8}
Yard OPS	1.68×10^{-4}	1.86×10^{-5}	1.69×10^{-5}	1.62×10^{-6}
Line haul	5.28×10^{-7}	5.87×10^{-8}	4.23×10^{-8}	3.50×10^{-9}

Units: Terminal OPS = Incidents/Shipment, Yard OPS = Incidents/Op, Line haul = Incidents per Car-Mile

4) The values from Table 8.8 are now disaggregated by spill size and then aggregated across accident types within each phase of operation, resulting in Table 8.9. Based on incidents involving ethylene and of LPG, the following approximate spill-size occurrences are used: minor spill 75%, severe spill 20%, catastrophic spill 5%. These are factored by the following, based on HMIR data:

- About 95% of dangerous environment leaks are minor and 5% are severe
- All catastrophic spills are assumed to result from derailments.

5) Ignition is assumed to occur in 10% of minor spills and 100% of severe and catastrophic spills. The values in Table 8.9 reflect this.

6) Table 8.10 results from applying 1-5 to the incident scenarios in the same manner that was done previously for highway incidents.

TABLE 8.10

INCIDENT RATES PER SHIPMENT (OR CAR-MILE) RAIL TRANSPORT OF LIQUID HYDROGEN

Phase of Operation	Description of Incident	Spill Category	% Allocation	Incident/Severity Level	Incident Rate
Loading	FVC Leaks - Splash or Fire	Minor	100	1 Injury	4.12×10^{-6}
	Liquid Phase leaks	Severe	50	Thermal Dia = 15 M	0.66×10^{-6}
	0.18 lb/sec. Vapor Venting	Severe	50	Negligible	0.66×10^{-6}
	Fuel - Air Explosion in Tank	CAT	100	Over Press + Frag = M	0.16×10^{-6}
Origin Terminal	FVC Vapor Release	Minor	100	Negligible	1.39×10^{-4}
	Liquid Phase Leaks	Severe	50	Negligible	4.22×10^{-6}
	Train Acc. 1,000 Gal/Min Spill	Severe	16.6	Thermal = 200 M	1.40×10^{-6}
	Train Acc. 11 lbs/sec Venting	Severe	16.6	Fireball = 50 M	1.40×10^{-6}
	Train Acc. 28,300 Gal Spill	CAT	100	Thermal = 1,000 M	5.50×10^{-8}
Destination Terminal	FVC Vapor Release	Minor	100	Negligible	6.94×10^{-5}
	Liquid Phase Leaks	Severe	50	Negligible	2.12×10^{-6}
	Train Acc. 1,000 Gal/Min Spill	Severe	16.6	Thermal = 200 M	0.70×10^{-6}
	Train Acc. 11 lbs/sec Venting	Severe	16.6	Fireball = 50 M	0.70×10^{-6}
	Train Acc. 28,300 Gal Spill	CAT	100	Thermal = 1,000 M	3.50×10^{-8}
Yard OPS	FVC Vapor Release	Minor	100	Negligible	1.68×10^{-4}
	Liquid Phase Leaks	Severe	50	Negligible	8.50×10^{-6}
	Train Acc. 1,000 Gal/Min Spill	Severe	16.6	Thermal = 200 M	2.81×10^{-6}
	Train Acc. 11 lbs/sec Venting	Severe	16.6	Fireball = 50 M	2.81×10^{-6}
	Train Acc. 28,300 Gal Spill	CAT	100	Thermal = 1,000 M	1.62×10^{-6}
Line Haul (Per Car-Mile)	FVC Vapor Release	Minor	100	Negligible	5.28×10^{-7}
	Liquid Phase Leaks	Severe	50	Negligible	2.12×10^{-8}
	Train Acc. 1,000 Gal/sec Spill	Severe	16.6	Thermal = 200 M	7.02×10^{-9}
	Train Acc. 11 lbs/sec Venting	Severe	16.6	Fireball = 50 M	7.02×10^{-9}
	Train Acc. 28,300 Gal Spill	CAT	100	Thermal = 1,000 M	3.50×10^{-9}
Unloading	FVC Leaks - Splash or Fire	Minor	100	1 Injury	4.12×10^{-6}
	Liquid Phase leaks	Severe	50	Thermal Dia = 15 M	0.66×10^{-6}
	0.18 lb/sec. Vapor Venting	Severe	50	Negligible	0.66×10^{-6}
	Fuel - Air Explosion in Tank	CAT	100	Over Press + Frag = 120 M	0.16×10^{-6}

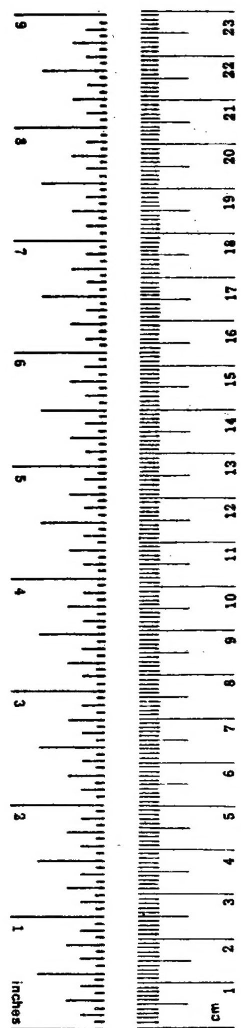
APPENDIX B

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

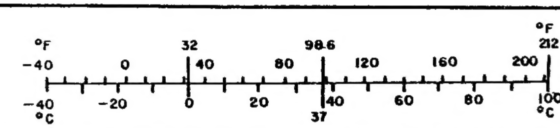
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



LIQUID HYDROGEN CONVERSIONS USED IN THIS ANALYSIS

1. One gallon of liquid hydrogen at -423^{O}F (normal boiling point) weighs .27 kg or .59 lbs and occupies 4.72 cubic meters, or .1333 cubic feet.

2. One cubic foot of hydrogen gas at 1 atmosphere and 68^{O}F weighs 2.36 grams or .005234 lbs.

3. One cubic meter of hydrogen gas at 1 atmosphere and 68^{O}F weighs 83.764 grams or 0.186 lbs.